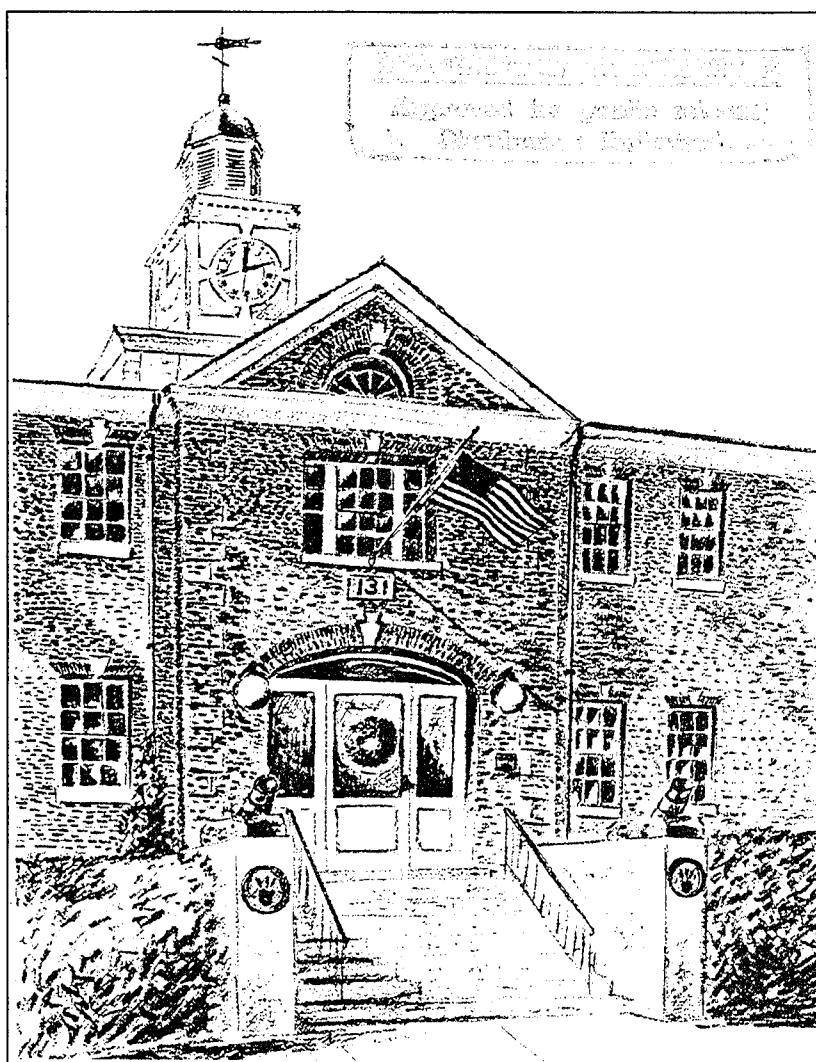


THE U.S. ARMY LABORATORIES
AT
WATERTOWN, MASSACHUSETTS

CONTRIBUTIONS TO
SCIENCE AND TECHNOLOGY:
A HISTORY



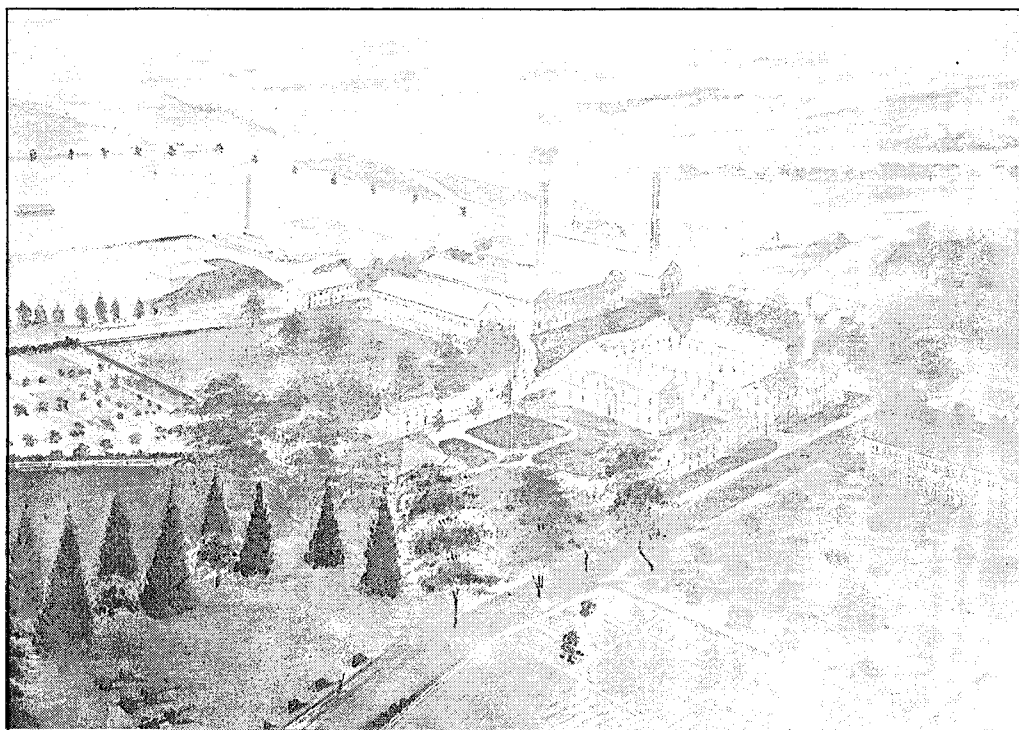
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Deborah E. Gray

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THE U.S. ARMY LABORATORIES
AT
WATERTOWN, MASSACHUSETTS

**CONTRIBUTIONS TO
SCIENCE AND TECHNOLOGY:
A HISTORY**



Frontispiece - A view of the Watertown Arsenal circa 1864

**Army Research Laboratory
Materials Directorate**
Arsenal Street, Watertown Massachusetts
August 1995

DEDICATION

This book is dedicated with respect and affection to George H. Bishop, who contacted and cajoled contributors, answered the author's technical questions with patience and informative explanations, wrote and revised sections, and most of all, held the project together. For George, the project truly became a labor of love. All of the personnel of the many Laboratories at Watertown are deeply grateful for his dedication to the project. The author's debt to him is immeasurable.

IN APPRECIATION

Special thanks are extended to two non-Watertown connected individuals. George A. Billias, Professor Emeritus at Clark University, may have sometimes left graduate students with the feeling that they had been rolled over by a tank, but his training gave me the tools to write about tanks. The friendship of James Edward Watters and the doors that he opened to my own research at the U.S. Naval War College gave me the courage to undertake this task.

PREFACE

In 1994 with the imminent closing of the Army Laboratories at Watertown, Massachusetts, several individuals whose careers had been spent at Watertown began to ponder how the essence of the laboratories and the record of the technical and scientific accomplishments could be preserved and transmitted. The concern was to capture the contributions which Watertown, especially in the years since the closing of the Arsenal in 1967, had made to the nation's defense and the furthering of scientific research in order to: provide those moving with the mission with a corporate history; to give those retired or now finding their Watertown and Army research careers coming to an end tangible memories; and to offer future researchers and historians guideposts to Watertown's uniqueness and significance. This book is the result of the vision, determination and hard work of those individuals. It is also the product of many individual interviews and topical histories.

It has not been possible to present a definitive or exhaustive history of every technical endeavor undertaken by the Army Laboratories at Watertown, nor does the length of each write-up necessarily reflect the level of activity which occurred in respective fields of research. Contributions were not forthcoming on all of the subjects which could have been covered. What the contributors, editorial board and author have attempted to do is to provide an indication of the depth and breadth of research at Watertown Laboratories during the past 30 years. The end result is a story not available elsewhere.

The final product has been shaped by both time restrictions and the availability of persons for interviews and written histories, given the difficult times of transition and relocation of laboratory functions. The chaotic conditions, and for many, the personal trauma of the closing of the Watertown facilities, have made the generous response to our request for interviews and topic write-ups all the more impressive. Without the support and input of many of the current laboratory researchers as well as numerous retired individuals, this book could not have been written. In testimony to individuals' continued identification with, and involvement at, Watertown, more than half of the project inputs were done by people no longer employed by the Army. All of the members of the Editorial Board were retired Watertown personnel. This gave the project the advantage of a perspective which was both firsthand and distanced. Unfortunately, time constraints, topical organization and the bulk of the finished product did not allow us to use papers as contributed. Contributors are, however, acknowledged in the bibliographic section of this volume. The original inputs, many of which contain much greater detail than what could be presented here, are being archived and are available to whomever may be interested. The sections in this book represent varying degrees of contribution, research and rewrites. Any omission or oversight in acknowledging contributions is regretted by the

author.

The author wishes to express a special debt of gratitude to the ARL historian, William T. Moye, and to the members of the book's editorial board: George H. Bishop, to whom this book is dedicated; Gordon A. Bruggeman; Robert Nathan Katz, who introduced the author to the project; Eric B. Kula; and Margaret "Jims" Murphy, the original contract supervisor. They conceived the project, developed a framework for the book, researched, wrote and rewrote, offered insightful criticisms, improved the factual accuracy and grammatical style of the book and enlivened meetings with humor when the task before us seemed all too daunting. We also are indebted to Mr. Kenneth F. Worth, Site Operations Director at Watertown, whose office underwrote the contract funding and who at all times was very supportive.

Even though the book's emphasis is on research activities, we nevertheless wish to acknowledge the vital role played by the many support people employed by the Watertown Laboratories over the years. Whether secretaries, security guards, custodians, payroll personnel, logistics officers, public relations professionals or engaged in myriad other activities, these individuals facilitated the performance of Watertown's mission. The accomplishments cited here would not have occurred without their support. In particular, the completion of this book within the allotted time owes much to the library and secretarial staff, especially Deborah Pakenham of the Technical Library, who located research materials, provided secretarial services, guarded the author's research files when the library underwent too rapid dismantling and in many ways made the author's research more enjoyable.

A special thank you is extended to the typist of the final product, Margaret Brodmerkle of Worcester Polytechnic Institute. She had originally committed to a project half this size, to be completed during the summer academic lull. Her professionalism, productivity, accuracy and cheerful disposition under a dual Army-academic crunch is to be admired.

Although a number of individuals were of critical importance to the initiation, execution and outcome of specific programs, early on in this book's evolution the decision was made not to focus on individuals but rather on the R&D process and end result as the product of team efforts and the laboratories themselves.* The pages which follow are a tribute to years of investigation, mentorship, cumulative interdisciplinary and interdepartmental work and to the spirit that was the Army Laboratories at Watertown.

Deborah Elrick Gray
September, 1995

* Because Watertown underwent many reorganizations, the name of the place will be referred to in the text according to its title in that time period.

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INTRODUCTION

Introduction

The Army's Laboratories at Watertown, Massachusetts have played a key role in the development of materials science and technology for the Army and the nation for 150 years. This has been chronicled in several past histories. For example, a review by the American Society for Metals* of major milestones in the development of metallurgy in America between 1917 and 1947 listed eight major milestones attributed to the Army's Watertown Laboratories. No other industrial, university or government laboratory was recognized as having been responsible for as many milestones in that period. In recognition of the laboratories' stature--the fact that Watertown researchers have "...developed and applied numerous significant metallurgical processes, tests and materials to the benefit of National Security"--the ASM designated the site an historic landmark in 1983. A year previously Watertown Arsenal had been named a national historic civil engineering landmark by the American Society of Civil Engineers. Published in 1977, A History of the Watertown Arsenal by Judy Dobbs chronicled these and other selected achievements through 1967. The purpose of the present work is to continue the chronicle through September 30, 1995, when the Army will transfer the materials mission to the Aberdeen Proving Grounds, Maryland, and cease operations at Watertown. The focus will be on the contributions to science and technology made by the Laboratories at Watertown. It will begin with a brief organizational history, and a short review of major accomplishments in the period from World War II to 1967, a period within the memory of retired staff. The emphasis will be on the period from 1962 to 1995, after Watertown became the Army's Corporate Materials Laboratory. A look at the activities of Watertown in the area of technology transfer will conclude the volume.

Organizational Evolution

For the first 120 years the Army's Laboratories at Watertown were intimately associated with and supported the manufacturing that proceeded at the Watertown Arsenal which was part of the Ordnance Corps. Their vision went beyond that to the development of new science and technology as detailed extensively by Dobbs. Gradually, the Laboratories began to take on a more corporate role. This began in 1954 when the Chief of Ordnance moved the Ordnance Materials Research Office (OMRO) from the Washington area in order to plan and administer supporting fundamental materials research at Watertown and other Army laboratories. OMRO became more than a planning group as the scientific staff

* Now ASM International.

also conducted in-house research. They, for example, operated the Army's first (and last) research nuclear reactor.*

Also in 1954, a new Metals Processing Laboratory, the General Thomas J. Rodman Laboratory, was established at the Watertown Arsenal. This laboratory was named for the Civil War Commander of the Arsenal. Two of Rodman's major technical achievements were the development of the Rodman Casting Process and the elucidation of critical parameters in the functioning of gun powder, both of which were accomplished in part at the Watertown site. The Rodman Casting Process markedly improved the life of cannons by chilling the bore, which produced an improved metal structure and a residual compressive stress in the bore. His basic studies on gun powder showed that the grains should be perforated to increase the burning surface. The mission of the Rodman Laboratory was to improve the quality of products, reduce their cost of manufacture, and provide material and/or methods for the production of strategic materials.

In 1962, the Army underwent a major reorganization in which the research, development and acquisition functions of the various Army Corps (Ordnance, Signal, Quartermaster, etc.) were combined to form the Army Materiel Command** (AMC), which was to have responsibility extending from conception to cradle to grave for the development of Army systems. Commodity commands were established to manage the research, development and acquisition (RDA) process for specific commodity areas such as missiles, armaments, tank-automotive and aviation. Each of the commodity commands had laboratories focused on R&D directly relevant to their mission. In key technology areas corporate laboratories that reported directly to AMC were also established.

As part of the reorganization, the Watertown Arsenal Laboratories (which had absorbed the Rodman Laboratory) and OMRO, were combined to form a corporate laboratory in materials, entitled the Army Materials Research Agency (AMRA). In this new role, AMRA was responsible for structural materials such as metals, ceramics, polymers and composites, but not for nonstructural materials such as textiles, explosives, paints, fuels and lubricants. Its principal missions were to:

- Conduct basic scientific research and applied research in metals, ceramics and other materials.
- Develop, adapt and improve materials for Army weapons and equipment, find substitute materials for those that may be scarce in time of war and set up materials specifications and standards.
- Develop testing techniques and provide technical

* The reactor was named for Horace Lester Hardy, the Watertown scientist who pioneered in the use of X-rays for industrial radiography.

** Materiel is to be distinguished from Material. Materiel refers to the weapons, equipment and supplies of a military force. Material is made from materials.

surveillance over AMC's testing and training programs.

The 1962 reorganization that placed the Laboratories at Watertown in an enhanced corporate role, weakened the position of the manufacturing operations at the Watertown Arsenal. The Army assigned responsibility for conventional weapons to the Rock Island Arsenal in Illinois, and Watertown was placed in a role supporting the Army Missile Command at the Redstone Arsenal, at Huntsville, Alabama. Two years later, on April 24, 1964, Secretary of Defense, Robert McNamara announced that the manufacturing operations at Watertown were to be phased out and most of the property would be declared excess, while AMRA was to continue in place. Following considerable public discussion, the Arsenal was closed in 1967, with much of its property transferred to the General Services Administration, which sold some 55 acres of the site to the Watertown Redevelopment Authority for public use and commercial development. The Army retained 36 acres for AMRA.

In 1967, an AMC study recommended organization of a center of excellence to focus and consolidate structural materials research and development, then spread over some fourteen laboratories. By orders dated July 1, 1967, The Army Materials and Mechanics Research Center (AMMRC) was established as a Class II Installation under the jurisdiction of the Commanding General, AMC. AMRA was discontinued, and its functions and employees transferred to the new center, whose activities now included mechanics and electronic materials work, as well as basic and applied research in metal, ceramics, and other materials. Plans called for the relocation to AMMRC of other activities, such as the Metallurgy Research Laboratory at Frankford Arsenal. The plan was to make AMMRC the Army center of materials research.

The first step in consolidation occurred in 1968 with the transfer to AMMRC of the research and exploratory development efforts in polymers and armor materials being conducted at the Natick Laboratories. Staff and equipment from Natick were moved almost intact into renovated facilities at Watertown, bringing together scientists, engineers, and technicians to conduct research on polymers and polymer matrix composites.

As part of these realignment activities, an extensive reconstruction plan was developed to provide expanded laboratory facilities, an auditorium, and other improvements. It was announced that transfer of programs, personnel, and equipment from other Army laboratories would be synchronized with the building program. However, little of the consolidation actually took place, largely due to Congressional action, as districts that would lose activities objected.

Although the consolidation of the Army's research at Watertown did not proceed beyond the initial group from Natick, AMMRC did realize the objective of the 1967 study to become a national center of excellence in structural materials research, as applied to Army systems. Its contributions to materials science and technology are detailed in Chapter IV.

From the mid 70s to the early 80s, the Army, however, was

still struggling with the best way to organize and manage its laboratories as part of the overall research development and acquisition process. These were a series of studies, including the Army Materiel Acquisition Review Committee (AMARC) in 1974; AMARC Revisited in 1979; and the Laboratory Effectiveness Improvement Program (LEIP) in 1983. These studies resulted in a period of organizational turmoil. As a result of AMARC, the commodity commands were discontinued and paralleled R&D readiness commands were established in the major mission areas of armaments, missiles, and mobility (air and ground). In 1976, AMC relabeled itself as DARCOM, the Development and Readiness Command. The new name continued until 1984, when AMC was reinstated. In 1979, a second AMARC study, AMARC Revisited, resulted in the R&D and Readiness Command being reunited along commodity/mission-area lines.

In the AMARC study two laboratories, the Harry Diamond Laboratory and AMMRC, received a backhanded compliment in that they represented "two typical R&D facilities whose capabilities and high-level potential are currently not adequately exploited in contributing to the Army's materiel mission."

The reductions in the defense budget in the post-Vietnam period resulted in budget squeezes and hiring freezes throughout the Army. In 1976, AMMRC faced the requirement to reduce by eighty spaces. Even though the center was successful in arguing against these cuts, and in the end actually gained ten spaces, it made for uncertain and anxious times.

In the fall of 1984, the new Commanding General of AMC, General Richard H. Thompson, proposed the concept of a Laboratory Command. Such a structure would consolidate and centralize management of AMC's corporate laboratories under a single Major Subordinate Command and would provide intensive front-end management of the acquisition cycle.

During the discussions which led to the formation of Labcom, the disestablishment of AMMRC was also discussed. A major factor was the age of the facilities. The center was characterized as a "consequence of historical evolution from Watertown Arsenal that has outlived its usefulness."

In the end, AMC decided against closure and put AMMRC in the new organization. Brigadier General James C. Cercy, Commander of Laboratory Command (LABCOM) (Provisional), suggested changing the name to highlight its expanded mission and movement beyond basic research. Cercy proposed Watertown Materials Laboratory, but AMC chose Materials Technology Laboratory (MTL).

However, these decisions did not secure Watertown's future. Indeed, in 1985 and again in 1986, the Secretary of Defense included MTL on lists of facilities that could be closed in order to save operating funds and rationalize the base structure. Many observers considered these actions to be political, with the Republican Secretary challenging the Democratic Speaker of the House, Thomas P. O'Neill, Jr., the member of Congress for the Watertown district.

Other studies were also ongoing, one sponsored by AMC

laboratory management, another by AMC resource management, and a third one by the Board on Army Science and Technology (BAST). AMC and DA studied several options, including dispersing the materials research functions to other AMC R&D activities versus relocating as an entity to new facilities to be constructed at Natick. Advocates of closure argued that realignment/relocation would reduce the expenses incurred in operating and maintaining an aging facility, one that needed an upgrading that would require very substantial resources. LABCOM agreed to relocation, if necessary, but recommended keeping the mission together.

During FY 86, the lab realigned and refocused its program to reduce the less critical activities and use the released resources to strengthen high-payoff, high leverage technology efforts. Critical technologies receiving increased emphasis included: composites and hybrids, advanced ceramics, advanced steel research, surface engineering and joining technology.

In May 1987, following a formal Army review, Under Secretary of the Army, James Ambrose, announced that MTL would be refurbished in place. The earlier \$22 million construction project, first approved in 1983, would be reconstituted into two phases, as follows: Phase I for 90,000 square feet of refurbished laboratory space at a cost of \$15 million; and Phase II for 30,000 square feet and general facilities upgrade costing another \$15 million.

Even so, in November 1987, Republican members of the House of Representatives included MTL on their potential base closure list. Then, in May 1988, the Secretary of Defense established the Base Realignment and Closure Commission (BRAC). During the summer, MTL was concerned that the construction project was slowing down and the money was slipping away. Then in December 1988, the Commission recommended closure of the Watertown site and dispersal of the materials mission. Metals R&D was to be transferred to the Armaments Research, Development and Engineering Center (RDEC) in New Jersey; ceramics R&D to join the existing ceramic facilities at the Tank Automotive RDEC in Michigan; and corrosion research to go to the Belvoir RDEC in Virginia. Watertown was to close by September 30, 1995.*

Once the Commission's recommendations were accepted by the President and by Congress in the summer of 1989, the fate of the Watertown site was sealed. LABCOM and MTL, however, strongly objected to the decision to disperse the materials mission. The dispersal would have destroyed the synergistic interaction of the various scientific and engineering disciplines which allowed MTL to successfully match materials to applications from the broad palette of possible materials and urgent Army systems needs.

* The rationale for this dispersal was flawed, however, in that it intended these missions to join existing activities which in some cases did not exist and it totally ignored several mission area responsibilities of Watertown such as polymers, composites and mechanics which were not intended to be eliminated.

Thus, in 1989, LABCOM leadership, spurred by the 1988 BRAC recommendations and by declining Army and AMC personnel and resources resulting from the end of the Cold War, developed plans to restructure the AMC laboratories by establishing a Combat Materiel Research Laboratory (CMRL), or Army Research Laboratory (ARL), as it was finally named. This CMRL/ARL concept, although successfully implemented in 1992, encountered considerable turbulence and competition in the various return and realignment activities. The important thing from MTL's standpoint is that the concept included a consolidated materials mission.

President George H. W. Bush launched the Defense Management Review (DMR) shortly after his inauguration in 1989. This exercise resulted in the formation of the Army Management Review (AMR) Task force by DA and, in the fall of 1989, the chartering of the LAB 21 study. Meanwhile the OSD undertook its own Lab Consolidation study.

The aim of the LAB 21 effort was to evaluate the Army's laboratories and RDE Centers and to lay out an organization to achieve the DMR goals of personnel reductions and dollar savings. Significantly, LAB 21 took as its logical starting point, the CMRL/ARL concept, which had been briefed to the Commander of AMC and given an initial go-ahead in August 1989.

Reporting in January 1990, the AMR Task Force, following a somewhat different strategy, recommended a package of personnel cuts and management savings. This package included the streamlining of AMC, which was directed to eliminate Headquarters LABCOM and to eliminate and/or consolidate its corporate laboratories. Nevertheless, the CMRL/ARL concept remained in the running as part of LAB 21.

About this time, it was announced that OSD would establish study teams to review possible consolidations and streamlining of the R&D laboratories and the test and evaluation facilities. As a result of this second OSD effort, the Army delayed implementation of LAB 21. Then, Congress initiated another round of base closure and realignment activities, passing legislation establishing BRAC 91, with members nominated in January 1991.

In April 1991, DoD published its recommendations to BRAC 91, adopting the LAB 21 proposal to realign Army labs. Under the scheme, CMRL/ARL would be consolidated, primarily at Adelphi and Aberdeen, Maryland, and the BRAC 88 mandate would be revised, with most of MTL relocated to the Aberdeen Proving Ground (APG).

In its report to the President, released in July of 1991, BRAC 91 endorsed the LAB 21 plan but directed the DoD to delay implementation until January 1992 in order to consider guidance from the Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories, established by the same law as BRAC. In its report, released in September 1991, the advisory Commission also accepted most of the LAB 21 scheme, stating that the proposed consolidations and realignments should begin in January 1992.

Orders establishing ARL (Provisional) were dated July 23, 1992. The activation ceremony was held at Adelphi on October 2,

and permanent orders organizing ARL were published on November 2, 1992.

Under the realignment forming ARL, MTL, less the structures mission, was to move to APG, and structures was to move to the Army Aviation Aerostructures Directorate collocated at NASA-Langley Research Center, Hampton, Virginia, expanding the mission at that site to form the ARL Vehicles Structures Directorate.

The new Materials Directorate, primarily the former MTL plus the 6.1 and 6.2 materials elements from the Belvoir RDE Center, was to conduct advanced materials R&D, including processing and manufacturing research, as well as testing techniques. As part of this transition, administrative activities supporting the Corrosion Prevention and Control/Corrosion Center of Excellence were to be transferred out. NDT training and certification, redirected by an earlier mission refocusing, would be completely transferred out of the new mission.

The bottom line from the standpoint of the materials people at Watertown was that, although they could not remain in Watertown beyond September 30, 1995, their struggle to prevent the wholesale dispersal of the materials mission was successful. They would become part of a consolidated Army Research Laboratory and a new world-class materials laboratory would be constructed at Aberdeen Proving Ground. Their location at a major Army facility would provide a measure of stability, and would allow positive synergistic interaction with other elements of ARL at Aberdeen and Adelphi, MD (only one hour's drive from Aberdeen). Watertown had long interacted with the other laboratories that had been consolidated into ARL, particularly with the former Ballistic Research Laboratory (BRL)* at APG, in the areas of armor and weapons development. Location on the same site would increase this interaction.

Throughout this period of obvious organization turmoil MTL/ARL-MD again continued productive research as detailed in Chapter IV. Important developments included: the Composite Infantry Vehicle Demonstration which led to Tacom's Composite Armored Vehicle Advanced Technology Demonstration Program; test methods for armor ceramics; tandem ceramic armor; improved helmet materials; ballistic blankets; gradient hardened armor steel; the Aircraft Modular Armor Program; Oxynitride glasses; SMARTweave; advanced ferroelectric ceramics; a new Presidential limousine; signature reduction; hardened materials for ballistic missile defense; and the development of a corrosion prevention and control program.

* Elements from BRL became part of the Weapons Technology, Computer and Information Systems, and Survivability and Lethality Directorates of ARL.

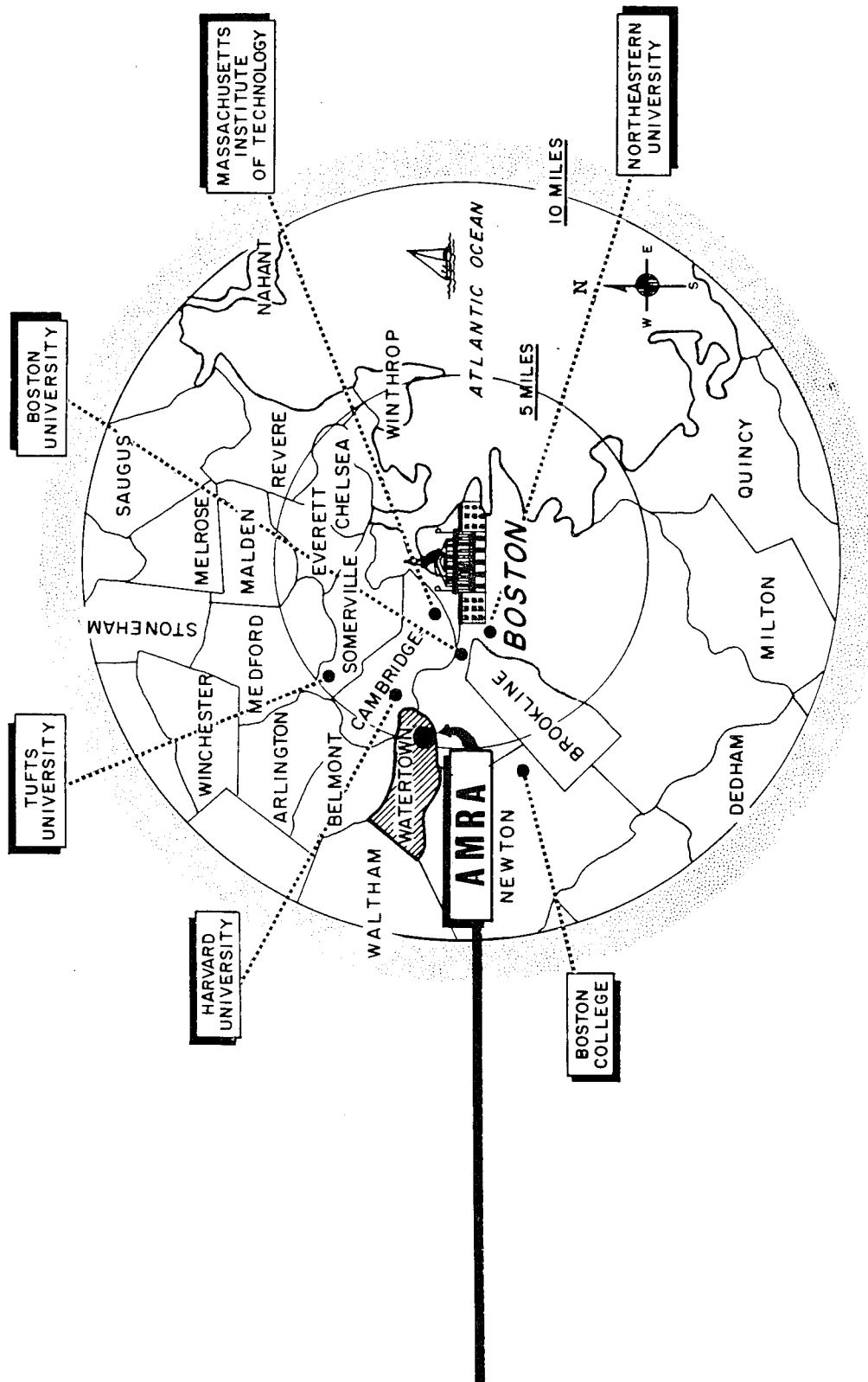
Keys To Success

As one hundred seventy-nine years of Army presence comes to a close at the Watertown Arsenal site, the importance of an illustrious series of laboratories on those grounds to the materials research needs of the Army can be traced to a number of interrelated factors. Over the years, scientists and engineers in ARL's predecessor agencies have been able to draw upon not only their own broad experience gained during outstanding professional careers prior to their employment at Watertown, but also upon the cumulative knowledge that comes from years of on-site and cooperative laboratory research and development. The multiple award-winning programs have generated a remarkable range of findings, which, in turn, can be brought to bear on new problems and challenges. For example, research and development in composites technology have benefited greatly from program advances in ceramics and in techniques for precision joining of large structural components.

Another important reason for the Watertown laboratories' leading role on the cutting edge of military technology has been their location. Watertown's close proximity to the educational and scientific research institutions and to the defense-related industries of the greater Boston area have enabled Army scientists and engineers to advance materials and mechanics research by quantum leaps. They have had unparalleled access to university research libraries, have participated in mutual problem-solving by sitting on university and industrial task force committees and have hosted seminars, featuring industrial and academic participants who are recognized leaders in their respective fields.

Experience, knowledge and location, however, must be made to bear fruit. As the preceding and following pages impressively document, Watertown researchers have consistently fulfilled their mission to be at the forefront of materials research and development, always responsive to new technological thrusts and the changing needs of the military. A multitude of Army agencies, as well as the other military services, federal agencies and industry have benefited from the pioneering experimentation and applications conducted under the aegis of ARL and its far-sighted predecessors.

THE EARLY YEARS



An important factor in the Laboratories' successes was Watertown's proximity to major universities.

INTRODUCTION

Several critical developments took place at the Watertown Arsenal Laboratory prior to 1910, including the Rodman gun development activities and the installation in 1881 of the Emery Testing Machine, a national testing facility establishing the viability of steel as a material. The acquisition of the Emery Testing Machine marked the laboratory's assumption of its function as a testing and experimental facility. It was not until 1906, however, that the wording of Congressional appropriations changed to provide authorization by law of "investigative tests." Therefore, from its establishment until about 1910, the WAL was largely engaged in making routine tests, such as measuring the strength of materials and structures. During Gen. Charles B. Wheeler's command of Watertown Arsenal, from 1906 to 1917, there began an increase in the amount of investigative and research work, until that type of work constituted the major part of the activities of the laboratory. In 1927 an article in Army Ordnance presented a four category classification of the work done at WAL: 1) routine testing, principally arsenal products and purchased materials; 2) private tests, made upon request of citizens and at actual cost; 3) control of metallurgical production processes in the manufacturing plant; and 4) investigative and research work.

This section of the history of the Army Laboratories at Watertown highlights several of the 20th Century accomplishments of the establishment, focusing on the years prior to the closure of the Arsenal. Our aim for these early years is not to be inclusive, but rather to capture the range and depth of research endeavors during those years and to demonstrate how later technological achievements built upon these early investigations and successes. Work in the early years will also be covered briefly in the introduction to subsequent sections.

INDUSTRIAL RADIOGRAPHY

The early production responsibilities of Watertown Arsenal motivated Arsenal personnel to pioneer in the application of radiographic tests to the solution of industrial problems.

During World War I, American industry, including the Watertown Arsenal Ordnance Department, suffered heavy losses in material and manufacturing time because of gross defects in steel castings. Defects not evident on the surface were frequently revealed in machining operations, causing rejection of partly finished work. In addition, unseen defects at the breech of big guns often caused them to explode when fired, killing or injuring their crews. It was evident that a reliable practical test method was needed to distinguish good castings from bad ones.

In 1922, stimulated by experimental work carried out at

Woolwick Arsenal, England, in which x-rays were used to photograph subsurface defects in steel, Watertown Arsenal installed x-ray equipment for use in routine inspection of foundry products.

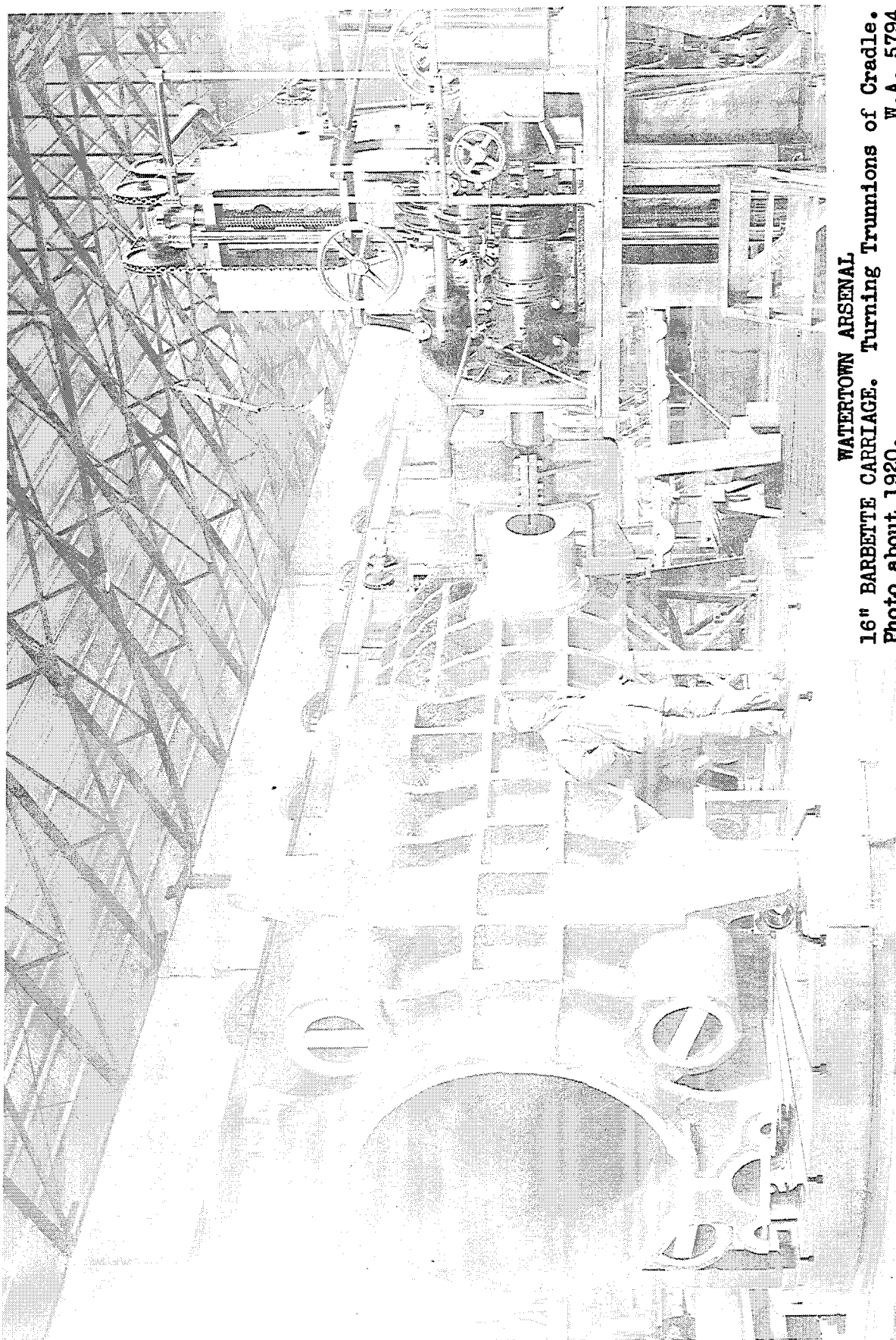
Initially, radiography was considered only as an inspection tool. It was found, however, that such use of the tests was not economical for two reasons: first, because the tests were expensive and time-consuming, the cost of x-raying sometimes being more than the original cost of manufacture of the casting; and secondly, because the inspection process was resulting in the rejection of more than half of the foundry output. Therefore, the Arsenal began to rely upon the use of radiographic tests for developing and improving foundry manufacturing procedure so that quality could be obtained by the proper manufacture of, rather than by the rejection of improperly manufactured material. Later the concept was extended to the application of radiographic tests to problems of production in the on-site welding industry.

In order to ensure that private industry defense production would be of acceptable quality Watertown Arsenal engaged in the education of industry in the benefits to be obtained from radiographic tests and contributed materially in the development of the methods of testing. For example, commercial concerns were permitted to send in their questionable castings to the Arsenal for examination.

By the late 1920s welding had been perfected to a point where its suitability as a fabrication method was well recognized. Watertown Arsenal then pioneered in the application of welding in the manufacture of gun carriage components to replace those previously made from castings. Much of the success of the new methods was attributed to the use of radiography in the development of the welding procedure and in controlling the soundness of the production weld.

The American Society for Testing Materials recognized radiography as a method of testing about 1925. In 1936 the Watertown Arsenal Laboratory played a prominent role in a Symposium sponsored by the Society that was devoted to x-ray diffraction and radiography.

Because of the interest shown in radiography at the 1936 Symposium, the American Society for Testing Materials set up a new standing committee devoted to the subject, Committee E7. The organization of this Committee and the chairmanship for many years was in the hands of Dr. H. H. Lester, who was in charge of radiographic research at the WAL. With international participation, the Committee served as a clearinghouse through which radiographic procedures were standardized for the United States and Canada. Radiography had been legitimized as a standard procedure, thanks to the early efforts of Watertown personnel concerned with quality control of production.



The challenge Watertown took upon itself in the late 1920s was to replace very large castings such as this with weldments.

CENTRIFUGAL CASTING OF GUNS

X-ray technology markedly improved the quality of steel castings, including gun castings. A further advance in gun barrel casting technology was the development of centrifugal casting in the late 1930s. This revolutionary change in gun manufacture had its origins in investigations conducted during the late 1920s at the WAL. Research culminated in the early 1930s under Dr. James Martin with the centrifugal casting process replacing the earlier slower forging method.

In centrifugal casting, molten steel was poured into a rapidly rotating mold which continued to rotate until the metal solidified, resulting in fewer casting defects. In addition, since the volume of molten steel was not sufficient to fill the mold, a hole was left down the casting center which obviated the need for drilling prior to machining the gun bore.

Centrifugal casting of guns offered other significant advantages, including: simplicity of manufacture, economy of material, rapidity of production and greater uniformity of product. The result was a decrease in rejectable castings. Because the centrifugally cast gun barrel was smoother than ones made by the forging method, the total machining time for finishing was reduced. Furthermore, producing guns by the centrifugal casting rather than forging method resulted in a materials discard savings of at least 30%. Less than half the quantity of raw materials was required to make the same number and kinds of guns.

Among the metallurgical advantages of centrifugal casting were: its segregation of carbon, making the proportional limit of the steel greatest at the bore where the stress is a maximum; higher tangential tensile and Charpy properties for the same composition; and sounder steel due to air bubbles, slag and other impurities being carried by centrifugal force into the gun bore where they could be machined away during the normal process of reaming and rifling. Because centrifugally cast guns could be cold worked to almost twice the bore enlargement possible with forgings, the gun weight was reduced, while strength remained unaffected.

The production in 1944 of the 100,000th gun tube by the centrifugal casting process focused attention on the major role which the Watertown Arsenal played in the manufacture of guns during World War II. Following Pearl Harbor, annual production jumped twenty-six fold from a 1940 base total of 1600 castings. Until private industry achieved sufficient conversion levels in July 1942, almost the entire Army gun tube program was successfully carried out by the Arsenal alone. National interest was shown by a Life magazine photo story which referred to the centrifugal casting method as "one of the proudest achievements of U.S. Army's Ordnance Dept."

The significance of Watertown Arsenal production figures to military morale was demonstrated by the fact that three National

Broadcasting Company microphones picked up the roar of the casting machines as the metal was poured for the 100,000th tube, in an Army Hour broadcast carried by short wave to American troops in every corner of the world. The human dimension of Watertown's wartime feat was captured in the letters former employees, now servicemen in combat, wrote home, telling of the pride and reassurance they experienced when they heard "our" big guns.

Other Allied nations also benefitted from Arsenal activities. In 1939 when President Franklin D. Roosevelt lifted the ban on sales of arms to foreign combatants, the Watertown Arsenal was manufacturing 90-mm gun barrels. By 1942 thousands of these guns were sent to British General Montgomery in Egypt, and their use was instrumental in routing the German Africa Corps. An interesting battlefield advantage which General Montgomery enjoyed was that he could fire captured German 88-mm ammunition from his 90-mm guns, while the Germans could not fire 90-mm ammunition from their 88-mm guns. This benefit continued for all the Allied forces throughout the entire war.

In 1944, the world's largest centrifugal casting machine, weighing over 88,000 pounds, was installed at the Arsenal, enabling production for the first time of ultra-heavy artillery tubes by the centrifugal casting method.

From laboratory innovation to combat operation, centrifugally cast guns were symbols of the indebtedness of the nation to the vision, continuous experimentation and patriotism of Watertown Arsenal researchers and manufacturing personnel.

FRAGMENT-SIMULATING PROJECTILES

During both World War I and World War II approximately 75% of casualties were the result of wounds from fragmenting munitions, primarily hand grenades, artillery and mortar shells. Developers of lightweight personnel and vehicular armor experienced difficulties in attempts to evaluate armor materials against the fragment threat. The general procedure employed at proving grounds was to place a circular array of several armor materials at various distances from a central burst point and to then detonate a fragmentation munition. Each armor sample had to be several square feet in size to ensure fragment hits. Fragments were collected behind the armor to determine their masses. Fragment velocities at various distances from the burst were estimated using standard air drag equations. Analysis of the resulting data yielded at best only a qualitative comparison of the armor materials. Furthermore, use of this method for acceptance testing of armor would be prohibitively expensive. Firing individual fragments from small arms weapons was possible using plastic discarding sabots, but because of the fragment's shape, its flight path was uncertain, resulting in as many misses as hits on the armor targets.

During World War II at the WAL, a homologous series of fragment-simulating projectiles was developed. These projectiles were made of steel and heat treated to simulate the average hardness of shell fragments. They were manufactured in several sizes, ranging in weight from 1.35 to 830 grains, and were designed to be fired from small arms weapons from .22 caliber to 20 mm in size. These could be fired at armor samples with the same precision as small arms rounds and at a variety of velocities to determine a ballistic limit (the critical velocity for perforation of the armor sample). This procedure yielded specific numbers for each armor material and fragment simulator size, and permitted quantitative comparisons of different materials. An armor sample on the order of one square foot in size was sufficient to determine a ballistic limit. This procedure also permitted use of the simple ballistic limit as an acceptance test in procurement specifications.

These fragment-simulating projectiles have been used for the past 50 years in research to develop improved armor materials, and in acceptance testing of armor during procurement to ensure quality compliance. WAL and its successor organizations have procured these projectiles and supplied them to other government agencies which use them for acceptance testing of armor.

ARMOR STEELS

As evidenced by the previous discussion, Watertown Arsenal was both a laboratory and a production facility. Personnel spent a good part of the war improving both cast and wrought steel armor, particularly for larger, more complex tanks and armored vehicles. Work was also done on aircraft armor. An outcome of the work was to put armor steel technology on a more rational footing. Up until the beginning of World War II, armor steel manufacture was considered an art. Each manufacturer had his own secret methods of alloy development, alloy use and heat treatments. WAL researchers established the fact that toughness and hardness are the two most important criteria in the manufacture of steel.

Toughness is that property which allows a metal to absorb energy and to deform plastically before fracturing, particularly under shock load or impact conditions. If a material lacks toughness it is unacceptable for many uses, especially military applications.

Watertown researchers discovered that certain alloy elements and the absence of impurities improved the toughness of steel. The selection of alloy would be dependent upon the thickness and type of structure being fabricated.

Because of the war effort, it was necessary to conserve several alloying elements. Armor was one of the major uses of alloys, so WAL initiated a major alloy conservation program, focusing upon the further development of leaner alloy steels for

armor use. This increased the supply of nickel, chromium, manganese and molybdenum for non-armor applications.

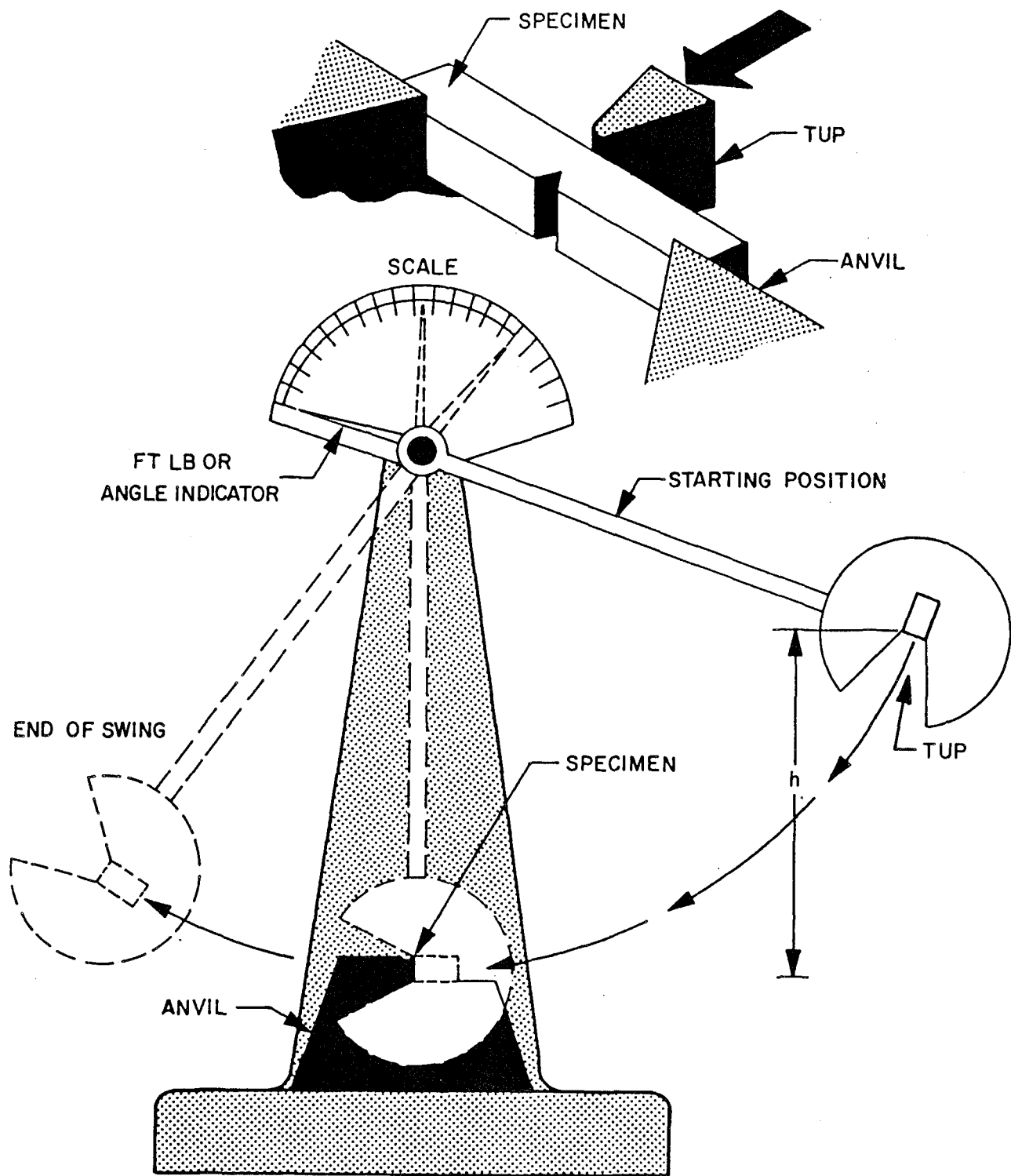
STANDARDIZATION OF THE V-NOTCHED CHARPY IMPACT TEST

To determine the toughness of these newly developed leaner alloy steels a simple test was needed to express quantitatively how the material would behave under a highly concentrated, suddenly applied load. To resolve this situation, the V-notched Charpy impact test was applied.

This test, developed by A.G.A. Charpy, a French engineer, consists of breaking a notched specimen, supported as a simple beam, with a weighted pendulum and determining the amount of energy absorbed by the specimen. The energy loss is expressed in foot-pounds and can be plotted on an absorbed energy vs. temperature curve to give the inherent impact strength (or resistance to impact loading) of the material at the temperature of the test and to determine the ductile to brittle transition temperature. By using the Charpy test one can ensure that armor steels are properly heat treated to contain the tempered martensitic microstructure necessary to sufficient toughness for armor use.

In 1914 WAL had become the first facility in the United States to own a Charpy impact machine, a 30 kilogram-meter machine. A second machine was installed in 1918 to permit the study of the importance of mechanical shock as a characteristic of gun steels. With a 300 kilogram-meter (2200 ft.-lb.) capacity, the machine was one of the world's largest. Original studies were conducted by Dr. Frederick C. Langenberg, who in 1926 was awarded the Henry Marion Howe Award by the American Society for Steel Treating, later the American Society for Metals, for his work. Later on, Dr. H.H. Lester received the same award.

Other smaller capacity machines were subsequently installed at WAL to study the susceptibility of metals to brittle failure. As indicated earlier, this information became more meaningful with the advent of World War II. While the failure of any design can often be related to a number of factors, more fully characterizing a material's properties and the relationship of those properties to service fitness became increasingly important. WAL personnel became convinced of the value of the Charpy impact test in correlating impact properties and the service fitness of gun steels, armor plate, breech rings and other ordnance components and the need for including impact requirements in federal specifications. A well documented case involved the fracture of hull plates in Liberty ships when operating at temperatures below the ductile-brittle transition temperature of the steel. While steel in the ships conformed to the applicable standards of the time, the Board of Investigation of welded steel merchant vessels found that "There are



SCHEMATIC DRAWING OF CHARPY TESTING APPARATUS

indications that the steel is deficient in a property not covered by the specifications." The report went on to use the Charpy test to relate notch sensitivity (absorbed impact energy) to operating temperature. Some of the steel used in the hulls was found to become highly notch sensitive at a temperature below the range of 40° to 80°F. The report also gives the impression that the significance of notch sensitivity had been studied in the laboratory, but its relationship to the ship failures was not well understood.

At the time, industry was concerned about the reliability of the test results. Tests on similar machines at different laboratories, or on differently designed machines at the same laboratory, were not reproducible.

To rectify this situation and to standardize Charpy V-notched impact testing, WAL early in World War II, and continuing into the 1950's, undertook to evaluate completely all aspects of the test. It was determined that variations in results could be caused by: the calibration and maintenance of the testing machine; the preparation of the test specimen; the technique used in conducting the test; and the quality and uniformity of the material being tested. When those variables were carefully standardized and controlled, accurate and reproducible results were achieved. In order to prove the reliability of the impact test high speed photography was done of tests run on various machine designs. In order to provide uniform test samples which could be used as a comparative standard material, a commercially available ultra-clean homogeneous steel was procured which was heat treated to provide different fracture energy levels and machined to exact specimen dimensions. Thousands of tests were conducted to establish desired energy levels and reproducibility, those being ± 1.0 ft. lb. or $\pm 5.0\%$, whichever is the greater.

The test data was then presented to steel producers and machine manufacturers. Recognizing the need for such a test, more than 52 test laboratories around the country agreed to participate in a series of round robin tests on samples prepared by WAL. Fifteen samples, 5 each at 3 fracture energy levels, were provided along with a questionnaire and specific test procedure guidelines. The broken specimens and completed questionnaires were to be returned to WAL for evaluation. When the average value for each of the three energy levels exceeded the established limits of ± 1.0 ft. lb. or $\pm 5.0\%$, whichever was greater, the broken specimens and completed questionnaires were analyzed against the knowledge that different model machines behaved differently when breaking the specimens. In cases where this evaluation of the broken specimens and the completed questionnaire gave reasons for average values outside acceptable limits, recommendations for changes in machine design and/or test procedures were returned to the company along with a new questionnaire and another set of standard samples for retesting. The WAL high speed photography played a major role in machine manufacturers' acceptance of recommended machine modifications.

The results of all the round robin tests were presented at

an American Society for Testing and Materials meeting and culminated in the acceptance of the WAL procedure as part of ASTM Standard E-23-56T and the insertion of an impact test requirement in many military specifications. WAL agreed to supply their standardized samples and questionnaires and to certify the acceptability of companies' impact machines to produce acceptable values to within 1.0 ft. lb. or 5.0%, whichever is the greater. The importance of compliance with ASTM Standard E-23 was demonstrated by the significant increase in machines meeting certification standards when E-23 was adopted by companies.

Although the standardization program was originally an agreement to supply reference specimens to DOD contractors to ensure that the Army would get good material, by the late 1950s Watertown was selling the standard specimens to whomever wished to buy them and to have their machines certified as capable of producing results in compliance with the ASTM standard. Because Watertown was the only source in the entire world for reference specimens, the standard became an international standard and was written into many material specifications, both defense and non-defense. One example of the test's prominence is the fact that Watertown machining and testing techniques were accepted as a standard by all NATO nations in May of 1958.

With the growth of the nuclear industry military hardware designers were interested in materials with much higher toughness than existing data was able to verify. Watertown personnel then came out with another set of calibration bars to be able to verify the machines in the 120 ft. lbs. range.

Advantages of the Charpy impact test include the facts that it can be run on any metal and at all temperatures. Unlike the European Izod test which is best done at room temperature, the Charpy test is relatively easy to do at anything from liquid nitrogen temperature to 500°, 600° or 700°F. It allows one to see how the properties of the material change at various temperatures and enabled the Watertown program to become a resource for researchers who wished to know either if a material was suitable for use in a certain temperature range or to ascertain if a material existed which could be used under specified conditions. Other features making the test desirable are its low cost and quickness to perform.

Since commercial sources or other government agencies were unwilling to provide the standardization service being provided by WAL for DOD contractors, ASTM requested that the service be made available to all interested users, both domestic and overseas. This gave tremendous visibility to WAL and its successors.

CAST STEEL TANK HULLS AND TURRETS

In other developments with origins in World War II work at Watertown Arsenal, steel casting technology was perfected to the

point where an entire tank hull or turret could be cast as a single unit. This technological advance was in response to the fact that the nation had insufficient steel rolling capacity to meet the wartime demands for commercial and naval ships in addition to armor plates for tanks. The inter-related nature of research developments at WAL made it possible to manufacture these castings from lean alloy steels with adequate toughness. In an example of early cooperation with industry, a metallurgical advisory committee, composed of experts from the steel foundries, was established to assist in guiding this effort and to implement the results in production.

ROTATING BAND COMMITTEE

Another prominent committee formed at WAL during World War II was the Rotating Band Committee. Comprised of members of the Army Ordnance Corps, the Naval Bureau of Ordnance, the Armour Research Foundation, the Franklin Institute, Brown University and Purdue University, the committee remained active in the postwar era. A rotating band is a ring of soft metal near the base of a projectile. It seals the propellant gasses and engages a gun tube's rifling, imparting spin to the projectile which stabilizes the projectile in flight. The mission of the Committee was to improve projectile rotating bands through a combined research and development effort.

Following World War II, the Applied Mechanics Branch at WAL became quite prolific. Group members used their analytical talents to explore phenomena in large rifled guns. When a gun is fired, the projectile starts forward and its soft metal rotating band is engraved by the gun's rifling. Significant stresses are present in the rotating band, and in the gun tube due to the propellant gasses and the projectile. The rotating band wears as the projectile travels down the tube, and the gun tube undergoes some amount of erosion during each firing. When the spinning projectile leaves the muzzle, the rotating band is suddenly subjected to a large amount of centrifugal loading, tending to cause the band to fly off.

Of great significance was the Rifling and Rotating Band Design Handbook, published in 1951 at the prompting of the Rotating Band Committee. Its object was "to present in handbook form data which is of use in the design of rifling and rotating bands." All aspects of gun-projectile interaction were addressed. Although this was originally intended as a preliminary handbook, a final handbook was never published. Instead, follow-on reports elaborating upon various areas were published throughout the 1950s and early 1960s. During the early 1950s, the Committee also published the Thick Walled Cylinder Handbook, in which static stresses in gun tubes (and similar objects) were calculated. These reports form "the bible" for stresses in guns and projectiles. They became the basis for

future work in fracture based design (fracture mechanics). This series of reports remains the definitive design guide to this day.

THE ARMY TITANIUM PROGRAM

One area of metallurgical research which spans the entire period from the end of World War II to the present is titanium. Its history as a subject of research at Watertown illustrates how Watertown researchers, in conjunction with contractors, successfully pioneered in titanium alloy development. To this day, Watertown researchers remain in the forefront of titanium research for military applications. The following discussion focuses upon early titanium alloy developments and the birth of Ti-6-4. The emergence of lower-cost titanium alloys is treated in the Light-Metal Armor section.

Prior to the development of the magnesium reduction process in 1945 by Dr. Wilhelm Kroll at the U.S. Bureau of Mines, titanium was considered to be too brittle to have any importance as a structural material. However, the Kroll process quickly changed that opinion and soon several companies, as well as the Department of Defense, were engaged in the development of light weight titanium alloys for structural applications. By the early 1950s each of the military services had massive programs ongoing in areas of its technical interest: the Air Force for gas turbine engines, the Navy for ship structures and the Army for armor applications to replace steel.

WAL, under the direction of Colonel Benjamin Masick, was charged with leading the Army effort. Over the course of the formal Army Titanium Program, which lasted approximately ten years, at least forty contractors became involved and well over \$6.5 million in contracts were let by WAL, most for under \$50,000. The major contracts went to three titanium suppliers, TIMET, Rem-Cru Titanium and the Titanium Division of Republic Steel, and to three principal research partners: Battelle Memorial Institute, NYU Engineering School and Armour Research Foundation (now IITRI). An equally large in-house program was conducted at Watertown, evaluating and extending contractor results and independently conducting research on titanium alloy development, metallographic and chemical analysis, mechanical property evaluation, heat treatment and various processing methods such as melting, casting, joining, forging and machining. Contractor and in-house efforts clearly built upon one another and contributed to the growing science base without which none of the programs would have been successful.

The very first Army research contract issued by WAL under the Army Titanium Program went to NYU Engineering School in 1948 for the study of titanium binary phase diagrams. NYU continued to receive Army support throughout the 1950s and by 1959 had developed and patented the alloy titanium- 6%aluminum-

6%vanadium- 2%tin (Ti-6-6-2), a high strength titanium alloy still in wide use today.

Perhaps the most significant result to come from the Army Titanium Program was the development of the alloy titanium- 6%aluminum- 4%vanadium (Ti-6-4), produced jointly by WAL and Armour Research Foundation around 1951. Under Army contract, Armour had investigated various ternary alloys based on additions of third elements to titanium- 4%aluminum. Of the many alloy combinations thus produced, the most promising was titanium- 4%aluminum- 4%vanadium. Speculating that increasing the alloy concentrations would produce further strength increases without seriously reducing alloy ductility, the WAL engineer in charge of the contract ordered Armour to produce two 20 lb. billets of titanium- 6%aluminum- 6%vanadium and titanium- 6%aluminum- 4%vanadium for evaluation by WAL. The mechanical properties of the titanium- 6%aluminum- 4%vanadium proved to be superior to those of any known titanium alloy, and a new space age material, Ti-6-4, was born. While titanium remained too expensive to be considered for most Army applications, the Air Force's gas turbine engine program benefitted enormously. The Army obtained the patent for the heat treatment of TI-6-4 in 1959.

The titanium- 6%aluminum- 4%vanadium alloy conceived by an Army scientist, first produced by Armour Research Foundation, first tested and evaluated by WAL, is to this day the most widely used of all commercial titanium alloys.

CONCLUSION

The preceding pages give some indication of the heritage to which AMRA and its successor organizations was heir. During this fruitful era of the 20th century the Army Laboratory and Arsenal made significant advances in non-destructive testing techniques and standardization and in the delineation of procurement acceptance specifications. Revolutionary changes in gun manufacture resulted in much improved materiel. Economy of production was achieved. Progress was made in materials characterization, and correlations were drawn to service fitness. These accomplishments were the result of both investigative leadership and team work. The outgrowth was a pride of accomplishment and a transference of technological knowledge to the private sector.

First and foremost, however, the Army Laboratories at Watertown have existed to meet the needs of the Army as demonstrated by WAL's multi-aspect response to the demands imposed upon it by World War II. The next chapter of this book chronicles Watertown research and developments in the field of high strength steels.

A NEW ROLE AS THE ARMY'S CORPORATE LABORATORY

HIGH STRENGTH STEELS

Introduction

For many years, the major thrust of the research and development activities of the laboratories at Watertown has been to develop and foster the use of higher strength, lighter weight materials for Army systems. In almost every application, whether equipment that must be carried by the individual soldier, weapons and vehicles that must be more mobile on the ground, or helicopters or materiel that must be airlifted, higher strength structural materials, which can be translated into lighter weight systems, have been a primary goal. At the time of World War II and in the years just after, high strength steels were the major material of interest. Since then, an increasing portion of the effort has been devoted to titanium and aluminum alloys, metal matrix composites, ceramics, and more recently to organic matrix composite materials. An examination of DoD budgets (and attitudes) today could lead one to conclude that metals are a material of the past, and that the future belongs to more exotic, "advanced" materials. Even staffing levels at the Watertown Laboratories have gone from a predominantly metallurgical laboratory in the 1950s to an organization where much less than one half the activity is concerned with metals. Nevertheless, steel is still the primary structural material in use today; many important developments in metals have been made through the years, and are still being made. Metals, and particularly steel, form an "advanced" material group, and will continue to play a leading role as a structural material in the foreseeable future. This topic was the subject of the 40th Sagamore Army Materials Research Conference in 1993, "Metallic Materials for Lightweight Applications."

There are a number of reasons for the continued interest in steels--cost, availability of the raw material, an industrial system already in place to process the material, reliability, ease of field repair, ability to be recycled, etc. Since steel has played such an important role in the history of the laboratories at Watertown, it is of interest to review some of these developments, particularly where Watertown has made important contributions.

At the outset it should be stated that the Army's interest in high strength steels arises from several separate but interrelated factors. The primary one is the greater load carrying capacity of high strength steels, which translates directly into reduced weight. A second factor is the higher hardness associated with higher strength, which generally yields better ballistic performance in armor plate, or the ability of components to survive ballistic impact. A third factor is the durability of high strength steels, leading to longer life in gears, bearings and components where wear is a concern.

Early Accomplishments

In the early years after the close of World War II, much effort at Watertown was devoted to improving the toughness of high strength steels. Experience has shown that it is seldom that a component has failed because of insufficient strength, or insufficient load carrying capacity. Rather, failures have often been sudden, of a brittle nature, caused by insufficient toughness in the steel. These brittle failures are often associated with the presence of flaws in the material, or stress concentrations in the structure, aided by an environment of low temperature or high loading rate. Examples of such failures include the well known cracking of Liberty ships during World War II, early gun tube failures and pipe line failures, as well as undesirable shattering of armor plate when impacted. Such failures are particularly undesirable because as they occur with little warning, they are difficult to design against, and no property easily measured in the laboratory could be used to predict their occurrence. Unfortunately, it was generally recognized that for high strength materials, there is an inverse relationship between strength level and toughness, with the highest strength steels being most prone to brittle failure.

The problem was of major interest to the Watertown Laboratories, and the extensive use of Charpy impact testing for toughness evaluation is an example of this interest. Impact testing over a range of test temperatures revealed that there was a transition from "tough" behavior at high temperatures to "brittle" behavior at lower temperatures, and that the temperature range over which the transition occurred varied from steel to steel. Thus two steels of similar tensile properties could have markedly different impact toughness at some temperature of interest, such as room temperature although the toughness at higher or lower temperature could be the same, i.e., the steels had different transition temperatures. Even though the reasons for this were not well understood, the Watertown Arsenal Laboratories took the important step not only of measuring the toughness, but of enforcing minimum toughness requirements on suppliers by inserting a toughness requirement in specifications. To the best of our knowledge, the toughness requirement for Armor Plate inserted in a 1949 revision of a 1930 specification for armor plate is the first use of a toughness specification by a DoD agency. Minimum toughness values had been required earlier, but only on a case-by-case basis. Including toughness requirements in the materials specification was a major development, the importance of which should not be underestimated. This was also the motivation for the Watertown Arsenal Charpy Calibration program (see The Early Years).

On an empirical basis, by requiring a minimum toughness at -40°C , which toughness value varies with the hardness or strength level, one has some assurance that at room temperature, and at

most colder temperatures at which the steel would be used, brittle fracture would be avoided. A further interesting point is that the toughness was specified in the transverse direction, which is the weakest direction. This gave recognition to the strong anisotropy, or directionality of properties, which existed in steels of that era because of the presence of elongated non-metallic inclusions in the rolled plate. These inclusions resulted from the higher impurity levels of steels in the 1940s, particularly oxygen combining with silicon to form silicates, and sulfur present as manganese sulfides. A considerable contractual effort was carried out for Watertown Arsenal Laboratories by Carnegie Institute of Technology to study the factors controlling the directionality of properties in rolled steel plate.

A significant contribution to high strength steel development came from studies of microstructure-property correlations in armor plate at Watertown Arsenal. This work showed that a microstructure of tempered martensite resulted in a lower transition temperature than low or high temperature bainite, at the same hardness level, and also in the avoidance of plate shattering during ballistic impact. This correlation provided the rationale for the toughness requirement in armor steel specifications. Without telling the contractor what composition steel to use or how to heat treat it, by specifying the toughness level, a good microstructure was ensured, and hence good service performance would result.

A particular problem that plagued consumers of steel in the 1950s was the phenomenon of temper embrittlement. In certain products, specifically heavy sections, after tempering a reduced toughness was found, even though the hardness and tensile properties were the same. The problem was of great concern to the electric power industry in heavy rotor forgings, as well as to the Army in gun tubes. Significant research work at Watertown and elsewhere revealed that this "reversible" temper embrittlement arose as a result of slow cooling through the range 900 to 1000°F after tempering at temperatures typically in the range of 1100°F. The embrittlement could be avoided by rapid cooling from the tempering temperature, or by the presence of alloying elements in the steel such as molybdenum, which prevented its occurrence. Later mechanistic studies revealed that the embrittlement was related to the segregation of impurity elements such as phosphorous, arsenic, antimony and tin to austenite grain boundaries in the embrittlement range. Because of this research, this phenomenon is no longer a problem for the Army, or industry in general.

Growth of High Strength Steel Research in DoD

Starting in the late 1950s and extending through the 1960s, there was a tremendous impetus to the materials industry provided by DoD and NASA funding. This large expansion in effort arose

largely due to the development of advanced aircraft, and the growth of the missile and space industry. Some of the expansion was aimed at jet engine and rocket nozzle development, but a major thrust was for structural materials for rockets and aircraft. In the early years, these were primarily metallic materials, including aluminum, titanium, and steel (although in recent years, an increasing share of the effort has been devoted to composite materials). The result was a tremendous perceived market for high strength steels, and the steel industry expended tremendous effort, generally using its own resources, to develop new alloys and new melting and processing methods, to supply this demand. Since the steel industry itself was seldom a direct government contractor, but rather served as a supplier to prime system contractors, it was generally not a recipient of DoD development contracts, nor could it use innovative funding sources such as the IRAD program, which was restricted to prime contractors. Thus they were forced to expend their own funds. Unfortunately, in many cases the perceived demand never materialized in terms of tonnage orders, so later the steel industry became wary of responding to DoD requests. This was particularly true when there was no obvious civilian market.

During this period of rapid expansion in materials R&D, the responsibilities of the three services and of NASA differed from one another significantly. NASA's role was primarily space craft, where materials were a limiting factor in performance. The Air Force mission focused on the development of advanced manned aircraft, which required advanced structural and engine materials. The Navy had a similar aircraft development mission. For both aircraft and space vehicles, materials were the critical factor in determining performance, but the cost of materials was often not a significant factor in overall system cost. Hence, NASA, the Air Force, and the Navy could afford to investigate the more exotic materials and processes in search of weight savings, regardless of cost, because the payback in terms of enhanced performance and higher payloads was so great.

The Army mission, on the other hand, was concerned with a far broader range of systems requirements which were unique to the Army and in which high materials costs could not be justified (with perhaps the exception of helicopter development). The Army was concerned with guns and projectiles, vehicles, armor, and all the other "mundane" equipment generic to land warfare, all requiring high strength materials for one reason or another, but all procured in such great numbers that cost containment was vital. For these Army-unique requirements, cost of materials was a much more significant factor. Moreover, the Army-unique requirements had little or no civilian counterpart, unlike the Air Force's aircraft development or the Navy's weldable ship steel research, for example. The result of these mission differences was two-fold. The Army's R&D efforts were channeled away from the expensive, more exotic materials toward those that were cheaper and more readily available. This explains the heavy emphasis on steel research at Watertown for many years. Hence,

the burden of support for steel R&D fell most heavily on the Army for most steel types and in a more limited way on the Navy for weldable steels for its ship structures.

The second result was that the flow of material R&D dollars went most heavily toward the development of those systems where materials cost was not a concern, i.e., to NASA, the Air Force, and the Navy. Although the Army had, in reality, a far broader materials requirement than either the Air Force or the Navy, it was allocated the far smaller portion of the DoD materials R&D budget. The result of this was that the Army did not (and could not) take the same leading role in research and industrial development as the Air Force and Navy, leaving the steel industry to depend upon commercial markets to drive whatever steel R&D it was capable of sustaining.

In spite of these very real fiscal restrictions and in reality a much wider materials mission, Watertown researchers participated fully in DoD, university, and industrial materials activities such as membership in ASTM and other professional society activities, NMAB committees and TTCP activities, and other similar government-university-industry forums. When needed, Army-unique requirements were highlighted, so that they would not be overlooked, and university, industry, or other government agency developments were brought quickly back to the Army to see how they could be adapted to Army needs. This "leveraging" of the Army's materials budget was an important adjunct to the overall materials program of the Army.

Role of the Watertown Laboratories

With this introduction, an attempt will be made to describe some of the accomplishments of personnel of the Watertown Laboratories during the last 35 years, and to try to relate them to other activities and trends within the government, industry and universities in the high strength steel area. Particularly in the early years of the period, there was a demand for higher and higher strength levels. This demand occasionally came from designers within DoD, including the Army, more often from contractors who wanted to supply lighter, and hence more high performance systems. Occasionally the contractor was allied with materials producers, who had their own newly developed proprietary alloy or process to offer. Especially in the period before fracture mechanics became well understood and accepted, the occasional lack of an understanding of the need for toughness, or the trade off between strength level and toughness was alarming. The role of the materials engineers was, on the one hand, to see how far strength could be raised without sacrificing too much in toughness for a given application, and on the other, to examine various means of pushing the entire strength-toughness curve out by various metallurgical means, so that higher strength-toughness combinations could be obtained.

Experience had shown that there were several methods of obtaining improved steels. One method involves trying to get the maximum properties out of existing steel compositions. This generally meant improving the toughness at a given strength level by using a "clean steel," i.e., reducing the content of certain embrittling elements such as phosphorous, arsenic, antimony or tin, removing deleterious gaseous impurities, oxygen, nitrogen and hydrogen, and removing or modifying the distribution of inclusions. These methods, together with a modified heat treatment to avoid thermal embrittlement, or possibly thermomechanical treatments, involve no new alloys or changes in nominal chemical composition of the steel. The other method is to develop new alloys, or compositions, which yield higher strength levels, yet with adequate toughness. Researchers at Watertown working along with their industry counterparts, have been active in each of the above methods.

From the late 1950s and into the 1980s a number of industrial developments were taking place to provide new melting and processing techniques to yield cleaner steel. Cleaner steels had the advantage of having a reduced inclusion content, which is desirable, since inclusions often were the sites of fracture initiation, thereby reducing toughness and particularly fatigue properties. Moreover, with a lower inclusion content, the undesirable anisotropy of mechanical properties was reduced. Various vacuum techniques such as vacuum induction melting, vacuum arc remelting, as well as vacuum ladle and casting techniques were developed to reduce gaseous impurities. This resulted in lower hydrogen contents, which reduced the tendency toward hydrogen embrittlement, a problem which becomes more serious as the strength level increases. Hydrogen has been a problem for years, whether arising from melting, furnace atmospheres during heat treatment, or processing such as electroplating, as evidenced by the number of field failures of high strength steel components. Considerable work was done at Watertown, particularly in the Corrosion group, to reduce hydrogen pick-up during electroplating, and to find other methods for protecting steel (see Corrosion).

Vacuum arc remelting has the advantage of reducing gaseous impurities, but also produces a finer solidification microstructure with smaller, more finely dispersed inclusions, which is reflected in improved toughness. A similar process, electroslog remelting (though not in a vacuum), produces a similar microstructure, because of the cooling rates inherent during solidification, and in addition removes sulfur, which otherwise would be present as undesirable sulfides.

As these techniques were developed by industry, Watertown personnel participated with producers in evaluating materials to determine the extent to which properties were improved, as well as in development programs to determine suitability for specific applications. Such steel were being considered for various munition, missile, helicopter and armor applications. Contractors using ESR and VAR steel on Army programs occasionally

encountered problems in supply, and changes in supplier might result in a proposed change from ESR to VAR steel. Watertown played a valuable role in carrying out several programs comparing the two processing methods. In one particularly useful program, a starting ingot of electric furnace grade 4340 steel was prepared, and a split heat was made, half remelted by ESR, and the other half by VAR. Thus a valid comparison of the two melting methods could be carried out. The results showed that there was little difference in mechanical behavior, although there were some subtle differences in ballistic behavior. For most applications either remelting method could be used, provided S and P contents were similar. These results were published and distributed to the appropriate contractors.

Those steel companies that did not choose to invest in remelting capacity, either VAR or ESR, made a sincere effort to produce better high strength steel by developing techniques to reduce phosphorous and sulfur. Generally, the phosphorous was reduced by slag practice, and sulfur by a special desulfurization treatment with lime. The value of these to Army programs can be seen in the improvements in steel armor, discussed in a following section. Watertown also played a role in encouraging the Army Research Office to fund some programs with a more visible, nearer-term payoff to the Army. In one particularly successful program with U.S. Steel Corporation, funded after Watertown recommendation, the option of using rare earth additions to minimize some of the deleterious effects of elongated sulfide inclusions in high strength steels was demonstrated. Toughness of the steel was improved, and anisotropy of properties reduced markedly.

Certain impurity elements such as phosphorous, arsenic, antimony and tin have been known to be detrimental to the toughness of steel, and are suspected of being responsible for "reversible" temper embrittlement, described earlier, and "irreversible" or 500°F embrittlement. As part of an in-house program studying the strength, impact toughness, and fracture toughness of high strength steels in the late 1960s, a mechanism was developed which explained 500°F embrittlement. For the first time, an explanation was provided which showed how trace amounts of these elements could segregate at austenite grain boundaries and at ferrite-carbide interfaces at these boundaries in a sufficient amount to cause the "irreversible" embrittlement.

One promising method of developing improved properties in steel was by means of thermomechanical treatments. Work at Watertown was initiated as a result of a contract with Prof. A.R. Troiano of Case Institute of Technology. This treatment involved the introduction of plastic deformation, "cold working," into the heat treatment process, so as to obtain improved properties. In the most common version, termed "ausforming," a steel is austenitized, then deformed at the austenitizing temperature or some lower, even subcritical temperature, under conditions that the austenite does not recrystallize (i.e., is cold-worked) nor does it undergo isothermal transformation. Then it is quenched

to form martensite. Results at Watertown and elsewhere confirmed the beneficial effects of this process. This martensite, formed from "cold-worked" austenite has significantly improved strength and adequate toughness.

A major contribution from Watertown researchers was to systematize the different types of thermomechanical treatments in several review papers, and to show the relationship between the "ausforming" type of treatment, formation of martensite in deformed austenite, and processes such as deformation of metastable austenite in stainless steels, and strain aging of martensite. This stimulated much activity in laboratories throughout the world, and at least two of the Watertown papers were translated (without permission) into Russian and published in Soviet journals.

The Watertown work was supported by several contractual efforts, particularly under a special program devoted to improved missile motor case materials, the so-called 6M program. Both research and prototype development programs were carried out, including the production of pressure vessels produced by sub-zero deformation of stainless steels. The major drawback of the "ausforming" process was the fact that the product was produced in the hardened condition, so that forming or extensive machining was extremely difficult. One development stemming from this work that did achieve a production status was dual hardness steel (see Dual Hardness Steel Armor).

In other programs, Watertown participated with the steel industry and systems contractors in developing or evaluating new compositions for specific systems. Our activities with Raytheon Corporation and the HAWK missile system are described elsewhere (see HAWK Missile System). For the accumulator, a newly developed hot work die steel, a modified H 11, was being used. This was an ultra high strength steel, which had the advantage of being air-hardenable. Unfortunately this steel exhibited rather low fracture toughness, and in addition was susceptible to stress corrosion cracking. After considerable pressure from Watertown, and to the dismay of the steel producer, the contractor switched to a standard 4340 steel, which was tougher and which was well accepted in the industry, although it was an oil hardening steel. Considerable work was done internally at Watertown to study the effects of impurity elements on the toughness of the steel. Published work by Watertown showed specifically how the elements sulfur and phosphorous deteriorated the toughness level, and that low, but commercially achievable levels of impurities, would lead to an improved product. These recommendations were followed, and the item has performed in a satisfactory fashion to this day, including during Desert Storm.

An example of where Watertown worked with the larger metallurgical community was maraging steels. This steel, developed by the International Nickel Company, offered tremendous potential, since it was air-hardenable, suffered no major volume change on cooling, and was soft and machinable in the unaged condition. When the steel was first announced, Watertown started

evaluation to see if the promised properties could be achieved, and where the material could find use. Watertown personnel presented their results at several Air Force-sponsored Maraging Steel Project Reviews, and verified that the 250 grade at least had adequate toughness and strength properties attractive enough for selective use. This material did find use in a number of cases, particularly missile applications.

In general, Watertown did not participate directly in alloy development of steels. There were some exceptions, however. In the case of gear steels, the Army had a particular requirement for steels in helicopter transmissions which could operate under severe field conditions, particularly oil starvation conditions for a limited time at temperatures above which the generally used 9310 steel would quickly soften and fail (see High Temperature, High Performance Gear and Bearing Materials for Helicopters). In addition to working with the prime contractor, Boeing Helicopter on Vasco X-2, Watertown evaluated a number of alternative materials, and directly sponsored the development at Climax Molybdenum of a new alloy, originally Amax B, later renamed MTL-2.

Another requirement which is Army unique was for high fragmentation steels for use in artillery projectiles. These are steels which must be tough enough to be safely projectile launched, yet sufficiently brittle to break into fragments of an optimum size for maximum lethality at the target. Usually these are high silicon or high phosphorous steels. Several steels were investigated, including PR-2, developed by Watertown investigators. A similar steel, HF-1, developed by Bethlehem Steel Company, is currently used, although there is little difference in properties between the steels. Watertown conducted extensive toughness evaluations of these steels to ensure adequate launch integrity.

In recent years, Watertown has been one of the sponsors of the Steel Research Group, a multi-institutional university/government/industry effort under Prof. Gregory Olson, formerly at MIT and now at Northwestern University. One of the aims of this program is to develop a steel which pushes the strength-toughness envelope to higher strength (hardness)-toughness combinations, specifically a steel at a hardness of RC 55 to 60 and a fracture toughness KIC of 60 to 100 ksi in. This would be a higher strength, higher carbon version of AF 1410, a 14 Co-10 Ni steel. The steel would find use for special ballistic applications, specifically for critical ballistically tolerant helicopter components (see Applications of ESR Steel), where there have been some problems with hydrogen embrittlement.

In this program, steels are being designed from first principles, using quantum mechanical and thermodynamic calculations. Particular goals are to design optimum carbide distributions for strength and improved toughness, optimum retained austenite distributions, and gettering of impurities for improved hydrogen resistance and interfacial cohesion. Watertown employees have played an active role in several aspects of this

program, including one Ph.D. program, and have authored or co-authored several publications on such aspects as decohesion mechanisms in iron by cohesive energy calculations, microvoid formation during shear deformation, and kinetics of carbide precipitation. Several Watertown produced alloys are under investigation, and a new steel developed as an off-shoot of this program is now commercially available. This alloy, AerMet 100, has been evaluated by Watertown for structural and ballistic applications and seems extremely promising for special applications.

Subsequently, world developments caused cobalt, a key alloying element in maraging steel, to become a scarce material, and to increase in price. Watertown personnel worked with the producer and Army contractors to see if cobalt-free grades of maraging steel could be developed and produced. These grades were evaluated by Watertown, and were shown to be adequate substitutes for the more expensive cobalt containing grades.

Armor Steels

A major need for high strength steels in the Army is for armor plate, where the higher strength and hardness translate into higher ballistic limits. Toughness has been a limiting factor, however, in increasing the hardness level. A novel way of overcoming the brittleness problem was developed at Watertown, as described in the section Dual Hardness Steel Armor. A laminated composite was developed, with a higher carbon high hardness front face, to shatter the projectile, and a lower carbon, lower hardness, tougher back-up layer to provide structural support in case of cracking of the front face. Two types of dual hardness were developed. The heat treatable grade can be delivered in the annealed condition, machined or fabricated as necessary, and then heat treated to the required hardness. This type of dual hardness steel was developed under contract to Watertown by U.S. Steel Corporation and Jessop Steel Company. It found a number of special uses as armor, and the material is still available commercially. A competing type of dual hardness steel was ausformed dual hardness steel, developed by Philco-Ford Company under contract to Watertown. This laminate is processed by thermomechanical processing, as described earlier, and is quenched to form the final product.

Watertown participated with the Army Research Office and with DARPA in supporting extensive research at Stanford Research Institute on laminated composites for armor. The effect of number of laminae and thickness ratio of hard versus soft layers were studied. Results confirmed that the two layer, 50-50 hard face-soft face composite was best, although a third soft front layer may provide some benefits in certain cases.

A major drawback of dual hardness steel was cost of the material itself, as well as increased fabrication costs where

complex shapes were required. Accordingly, efforts continued to improve the properties of conventional armor. In a cooperative study with the Ministry of Defence in the United Kingdom, a program on improved special processing of armor plate was initiated. This involved the directional solidification of the steel, which resulted in a finer dendritic arm spacing, less segregation, and finer and more dispersed inclusions. Some success was achieved, although the processing cost was high. Later the effort was extended to a special high temperatures homogenization, in order to reduce segregation. This was not successful. At about this time, electro-slag remelted (ESR) steel became commercially available in the United States and in the UK. Because of the inherent solidification rates in ESR, the same results as directional solidification could be achieved on an industrial scale at a more affordable cost.

Considerable effort was devoted to ESR by the laboratories at Watertown. A laboratory size ESR furnace was installed and used for investigating such things as the effect of slag chemistry on sulfur removal. In addition, Watertown personnel worked with steel producers and Army contractors to provide commercial scale ingots of ESR steel for evaluation. This included such things as procuring rectangular ESR molds, in order to provide rectangular ingots, a better shape for processing to plate than the circular ingots normally used. The ESR process did succeed in providing a lower sulfur steel with an excellent solidification structure. Although this resulted in a superior armor, ESR never achieved commercial acceptance for several reasons--a combination of increased cost, the lack of a new system at the right stage of development as a demonstration vehicle, and successful efforts by the steel industry (those without ESR capability) to provide lower sulfur steel by other means such as ladle desulfurization, or by use of rare earth additions, which produced hard, globular rare earth sulfides rather than the long, stringered manganese sulfides normally found.

One area where ESR did find a use for the Army is described in the Section on Applications of ESR Steel. McDonnell Douglas Helicopter, on becoming aware of the excellent properties of ESR steel, approached Watertown for advice on the use of ESR steel for a number of ballistically tolerant components for the Apache helicopter. The efforts to use ESR steel for this application were not without technical problems, however. The components were generally machined out of thick plate, and properties in the through thickness direction revealed some extremely puzzling results. There was good fracture toughness, adequate Charpy impact toughness, but almost zero reduction of area in a tensile test. Watertown personnel worked with Prof. Gregory Olson of Northwestern University, the steel producer, and the contractor to solve the problem. Experiments at Watertown showed that stress corrosion cracking occurring during the tensile test along inter-dendritic boundaries was the cause of the problem. In a paper published in Metallurgical Transactions, authored by Prof.

Olson and the Watertown investigators, the phenomenon was characterized and means of minimizing it were discussed. Unfortunately, this has been a limiting factor on using the steel at the highest hardness levels.

Meanwhile, attempts to improve rolled homogeneous armor produced under specification MIL-A-12560 have continued, since this is the most used armor material. Researchers at Watertown have been taking advantage of improved steelmaking and processing methods to produce better armor. As a result, impurity contents, particularly sulfur and phosphorous, have been reduced from 0.04% of each element in the 1960s and early 1970s to 0.015% S and 0.025% P today, and even less in high hardness steel armor, MIL-A-46100, 0.010% S and 0.020% P, or ESR plate, MIL-S-46188, 0.003% S and 0.008% P. These purer steels have allowed the toughness requirements in the specification to be increased significantly, yielding tougher armor, and open up the possibility of using higher hardness levels than before. This has been an evolutionary development that is still going on. The result is that armor plate today is a vast improvement over what was available in the post World War II era or even 25 years ago.

Mechanical Behavior of High Strength Steels

As the need for higher and higher strength levels arose, it became apparent that there were shortcomings with the Charpy impact test for measuring toughness. At the highest strength levels, the toughness values became so low that the test was no longer sensitive for comparing the toughness of different lots of steel, and a good part of the energy expended in breaking the specimen was elastic energy, not the plastic energy necessary to initiate a sharp crack from the machined notch, and propagate it through the specimen. A further shortcoming was that many of the materials and products were in sheet form, precluding the use of the standard Charpy specimen and further lowering the measured energy values. The major drawback was that the Charpy toughness value was in reality a comparative value, which could not be used directly in design calculations. During this period fracture mechanics was developed, whose aim was to provide a technique for relating a critical flaw size (crack length) and an applied stress level, to a fracture toughness value K_{Ic} , which was a materials property not unlike the Charpy toughness. Ideally, this would provide the materials developer with a toughness value to be used for comparative purposes, the designers with a stress value to use with various flaw sizes that could be used in design calculations, and inspection personnel with a target flaw size to detect in the final product.

The technology of fracture mechanics was developed under the auspices of ASTM Committee E 24, and subsequently several subcommittees. Although there was a heavy bias in the committee make-up toward missile and aircraft applications, and much of the

early leadership came from the Navy or NASA, Watertown personnel participated through the years in various committees and subcommittees. A problem, especially in the early years, was that fracture toughness tests were only valid at the very highest strength levels, above that utilized in most Army equipment.

The work of Oscar Bowie in the Applied Mechanics group was of particular importance to the early development of fracture mechanics. Using conformal mapping techniques, he was able to study the stress distribution around cracks in various complex geometries such as gun tubes. This was done in the days before computers were generally available. This is described in the section "Fracture Mechanics at Watertown." Others in the group made valuable contributions in developing techniques for determining the parameter K_{II} , the critical stress intensity factor under shear conditions, as well as applying fracture mechanics concepts to various special geometries of interest and to the problem of fatigue crack growth and the influence of such factors as average stress or intermittent overloads.

The material groups at Watertown were primarily concerned with techniques for measuring fracture toughness and using the toughness values as a tool in rating materials. Although the test was not fully standardized, it was used to study the effect of composition and processing variables. One problem was to determine the crack length in a standardized precracked specimen during the test, and particularly at pop-in. The recommended method in the early days was to use ink staining. This had drawbacks, because the ink itself could influence the fracture load, and the method could not be used at cold or hot temperatures. An electric potential technique was developed at Watertown, which was based on early erroneously termed "resistance" measurements. In this technique, the voltage drop across a crack was measured and recorded, which could be directly converted to the crack length. The technique was adapted to fatigue testing, and could be adapted to various geometries. This test has been taken over by others, and is still in use today as one of the major methods of measuring crack length in a fracture toughness test.

Even tensile testing of high strength steels could pose challenges. Because of the high stresses necessary to cause plastic flow, plastic instabilities could occur during the test, giving rise to sudden load drops, serrated yielding, and localized necking. Earlier work at Watertown had been done to study true stress-strain behavior of metals. This required diameter measurements during the test, and a recording diameter gage was developed, which could measure and record the minimum diameter during the test. Temperature capability ranged from 4.2°K (liquid helium), to several hundred degrees Fahrenheit. The testing facilities at Watertown were as advanced as any in the country at the time. With this equipment, Watertown investigators were able to relate the occurrence of serrated yielding during testing of ultra high strength steels to localized plastic flow (necking) at a single location during the

test, and also to demonstrate that serrated yielding at temperature of liquid helium could occur by a number of common plastic flow mechanisms, and was not uniquely related to twinning or martensite formation, as many in the scientific community had claimed.

Conclusion

Steel remains the foremost structural material in the world, and was a dominant force in the economic development of the United States. Steel has been, and is, used everywhere, and in large tonnages. This has meant, however, that on this scale the Army has always been a small consumer of the nation's steel production. Hence one might not expect that the Army would be a major influence on the developments in steel technology that have taken place over the years. Yet it is the ever more stringent requirements placed upon steel technology by Army and other Defense systems that has pushed the technology to its present state. Watertown's role in this development has been crucial and varied, ranging from direct contributions to the technology through its in-house and sponsored research activities, to the interpretation of Army systems needs in terms of materials requirements understood by the industry, to the evaluation of technological advances, regardless of where they were made or for what reasons, that enabled Army systems developers to use advanced steels and steel technologies with confidence. While Watertown has only infrequently been the leader in the development of advanced steel technology, it has been responsible for "stretching" the technology to meet ever increasing specification requirements and for creating a market for advanced steels through its advocacy role within the Army.

ARMOR MATERIALS

Introduction

Watertown has been involved in the development of armor materials for more than 60 years. The earliest references to armor materials are found in writing by Brig. Gen. T.C. Dickson and appear to refer to steel. In a 1928 history, he notes that the Arsenal was equipped to produce up to 600 tons of thin armor plate per year. In a 1927 article in Army Ordnance, he reviewed the principal investigative and development work conducted by the Laboratory. The list was started with a study of 1/4, 3/8, and 1/2 inch thin armor plate "made in this country and abroad of various compositions and subject to different heat treatments," which showed that "the resistance to penetration is more dependent on the final structure of the metal than on chemical composition." This conclusion stands today.

Further work on steel armor was conducted in the 1930s, and in 1935 cast armor was first successfully produced by the Lebanon Steel Foundry to specifications developed at Watertown.* This led, in turn, to the development of the technology vital in World War II for the casting of tank hulls and turrets. Watertown also continued its work on rolled plate armor. As the U.S. prepared for World War II, it became clear there would not be enough alloying elements to meet all the war demands for steel plate. Watertown metallurgists initiated an alloy conservation program for rolled armor in which scarce alloying elements would be replaced by more readily available ones. This led to a rolled homogeneous armor (RHA) specification, which in modified form, is in use today. The simultaneous development of the Charpy Impact Test (see Standardization of the V-Notched Charpy Impact Test) was critical to both of these developments in cast and wrought armor steel, as will be shown. The RHA specification has been the mainstay of Army armored vehicle procurement since World War II and is vital to the procurement of the M-1 Abrams Tanks today.

Late in World War II and subsequently, although efforts continued to improve steel armor and still do, attention turned to other classes of materials. Studies of fibers, fabrics and plastics for personnel armor started in the 1940s; aluminum and titanium for lightweight vehicles in the 1950s; ceramics and resin matrix composites in the 1960s. Watertown contributed to all these areas and led most, as detailed in the following section. In 1965, Watertown was designated as the Lead Laboratory for Light Armor in recognition of its pioneering work in ceramic armor.

* This was one of the "milestones of Progress" for which Watertown was cited in the January 1948 issue of Metals Progress.

The critical expertise that Watertown brought to the armor area was an understanding of materials, and how materials interacted with the various threats, so that the material with the optimum properties to defeat the threat (or threats) could be selected off-the-shelf or developed as needed.

Ceramic Armor

Introduction

Inorganic nonmetallic materials have long been used as protective shields against missiles and other flying objects. From city and castle walls, to the concrete emplacements of the Maginot Line of World War II to the concrete ICBM silos of the present time, ceramic-type materials have been universally recognized for their protective capabilities. In these applications mass of material rather than mobility was the major defense mechanism.

The advent of modern warfare put the emphasis on mobility to move men and materiel quickly around the world, and to be able to quickly concentrate force in battles once you move in-country. This resulted in an emphasis on light weight. Interest shifted from brick, stone and masonry to the use of metals for protective materials for mobile systems, a trend reaching from armored knights on horseback, to ironclad ships, to tanks and other combat vehicles. The growth in penetrating power of weapons, however, required increasing thickness of monolithic metals, causing increasing systems weight. The ultimate in mass vs. mobility design tension was reached at the end of World War II with the development of a 95-ton tank directed at breaching the Siegfried Line. Two were produced but never saw combat.*

To avoid this growth in weight the armor community looked to new materials and novel designs and combinations of materials. It was in this climate that Watertown researchers returned to ceramics, despite their brittleness, because of their low density and high hardness and compressive strength. The effort was successful as detailed below.

Since the advent of lightweight ceramic armor in 1962 Watertown has played a central role in the development of ceramic and armor ceramics. Largely due to Watertown research efforts, lightweight ceramic armors for protection against small arms fire, long rod penetrators and shaped charges are available for personnel, aircraft and combat vehicles. The Army Laboratories pioneered in the development of ceramic armor materials research, composites for back-up materials, modular armor and transparent armor. This section details Watertown's contributions in

* One can be seen at the armor museum at Fort Knox.

developing ceramic armors for aircraft/crew protection and combat vehicles.

Aircraft/Crew Protection

During the Vietnam conflict the main threat to U.S. Army personnel utilizing the slow-moving, low-flying helicopters was the constant danger posed by 7.62-mm small arms ammunition. The personnel armor materials which were developed for protection against shell fragments, which had been the primary cause of casualties during World Wars I and II, were not very effective against small arms ammunition. The heavy weight of conventional metallic armors had long discouraged its use in aircraft/crew applications. What was needed was a significant breakthrough in lightweight armor.

Analysis at AMMRC indicated that high elastic modulus, high hardness, low density armor materials could induce shatter of AP projectiles, and this might lead to lightweight armor systems. Several ceramics were known to have such a combination of properties and around 1962 aluminum oxide faced composite armor meeting the minimal ballistic needs for helicopter armor was developed by Goodyear Aerospace Corporation and put into almost immediate production.

Scientists at AMMRC in late 1964 first demonstrated a boron carbide faced composite armor system which proved to be the most ballistically efficient, usable lightweight armor system to be developed at the time. Boron carbide is the hardest and [has] the lowest theoretical density of all the armor ceramics. Because of the inherent fracture peculiarities of ceramics, a backup must be used in the armor system to support the ceramic during the initial phase of attack by inhibiting tensile failure in the ceramic and later, to protect against both the fragments of the projectile and ceramic and the remainder of the projectile which still possesses kinetic energy. The composite backing absorbs the residual energy transmitted by particles and shock wave through the mechanisms of large gross deformation. Boron carbide backed by glass reinforced plastic would defeat the 7.62-mm AP threat at a little more than one quarter of the weight of steel armor. Materials specifications for the procurement of ceramic/ composite armor were developed at AMMRC and standardized for use within the Department of Defense.

In order to expedite use of ceramic armor in Vietnam, AMMRC, in a special assignment from the Commanding General of the Army Materiel Command, determined both the armor requirements for each airmobile division and the national production capacity of boron carbide. When it became evident that production capacity was inadequate to meet the Army need within a reasonable time frame,

AMMRC, working together with Natick Laboratories,* and private industry, developed a whole new industrial capability for fabricating large complex curvature boron carbide shapes for aircrew torso shields and seats. Curved monolithic plates eliminated the problem of inherent vulnerability of the joints between the flat tiles used in earlier breast plates and permitted the protection of a larger body area.

The development of boron carbide composite armor went from laboratory demonstration, through industrial scale-up and process development, to fielding in about two years! It was one of the most rapid exploitations of a new technology on a large scale basis on record. Over 30,000 sets of aircrew torso shields were produced and sent to Vietnam. Hundreds of lives were saved and many missions completed.

AMMRC continued to conduct ceramics research to improve the ballistic protection afforded by the boron carbide composite armor and also tested materials for the rear component of the armor. In particular, new back up materials such as Kevlar made possible even more weight efficient systems.

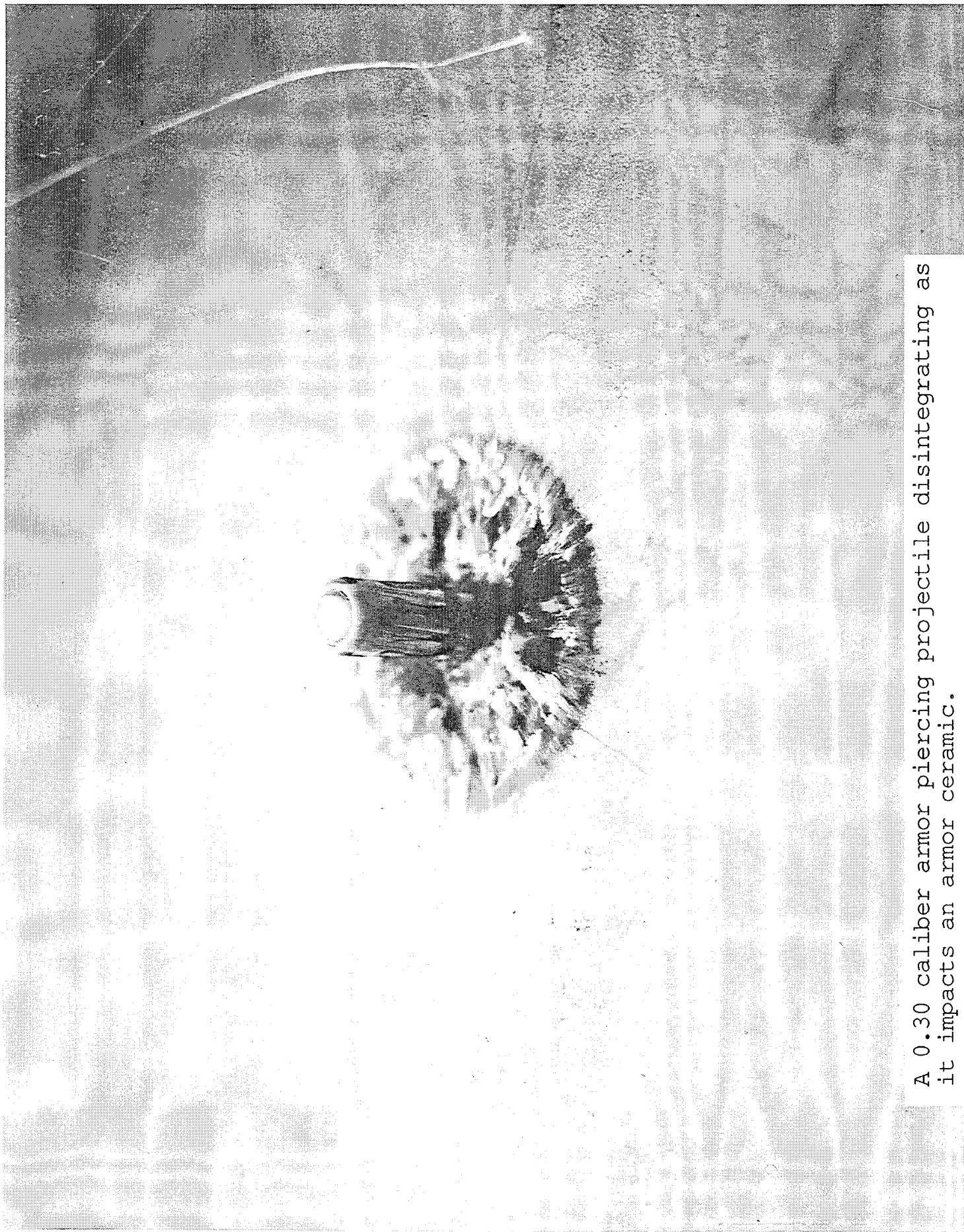
Seats in combat helicopters not only have to be ballistically protective, they have to be crashworthy. The boron carbide/Kevlar seat for both the Blackhawk and Apache could defeat small arms projectiles at close range and could also withstand high impact G loads. The armor is currently used in the Army's APACHE and COBRA helicopters and in the CH54, OH-6A and OH-58 helicopters for protection against armor piercing rounds and high speed fragments.

In other ceramic advances, aluminum oxide faced resin bonded laminates of E glass fiber or Kevlar 29 were utilized for the protection of critical aircraft components.

In late 1986 and early 1987, Watertown engineers proposed a program to investigate a new concept for aircraft armor to the Joint Technical Coordinating Group on Aircraft Survivability (JTTCG/AS). The technical basis for the program was extensive research and development on armor materials conducted by scientists and engineers at Watertown. The philosophy guiding the program marked a departure from traditional aircraft armor design philosophy which emphasized integral hardening and eschewed the use of appliqué armor because of the weight penalty it accrued to the aircraft. The new idea emphasized modular design of armor panels which could be rapidly installed or removed and tailored to meet a field commander's immediate tactical requirements.

Modular armor is defined as armor that can be installed quickly for hostile operations, replaced when battle damaged and removed when not needed. As armor technology improves and threats become more severe a module's ballistic performance can be upgraded without the need to retrofit.

* Natick had systems responsibility for personnel armor. See section on that topic.



A 0.30 caliber armor piercing projectile disintegrating as it impacts an armor ceramic.

Since modular armor is easy to install and remove, modular armor systems can be designed to complement an aircraft's mission configuration. Modular armor provides a means for protecting not only crew members and flight critical components, but also passengers. For example, an aircraft flying troop transport or medical evacuation in areas of high threat density, such as the forward edge of battle, could be up-armored to provide increased protection. Flight critical components could be similarly up-armored. When the aircraft's mission environment does not possess a high threat density, the armor modules can be removed and replaced with lighter, load bearing members, thus realizing fuel and/or weight savings.

The Aircraft Modular Armor Program consisted of two major phases. The first phase included the design of several modular armor prototypes. The second phase involved fabrication and ballistic evaluation of two generations of prototype modular armor systems. Phase I was completed during fiscal year 1990 and was accomplished with support from Boeing Military Airplanes of Seattle, Washington. The phase II fabrication and testing team consisted of representatives from the Army Research Laboratory, Ceradyne, Inc. of Costa Mesa, California, Vantage Composites, of San Diego, California, and the Southwest Research Institute, San Antonio, Texas.

The prototypes consisted of armor panels fabricated from ceramics and Kevlar composites, an airframe section fabricated from advanced composites, and a fuze shield to pre-detonate high explosive incendiary rounds. The program, which ended in 1993, was the first armor research effort to produce a system specifically designed to defeat both the 12.7mm API B32 threat and the 23mm HEI MG25 fuze threat. The program managers demonstrated the soundness of new design concepts to reduce significantly damage and armor weight requirements. The program also generated valuable information regarding the response of a composite airframe outfitted with armor to ballistic impact and, by virtue of field level breakdown and rebuild to original specifications, the considerable worth of designing the modular armor concept into next generation aircraft.

Ceramic Armor for Vehicles

As pointed out in the previous section, ceramic armor found almost immediate application during the Vietnam War in the protection of helicopter crewmen. This has not yet happened in the case of ground combat vehicles. There are a series of reasons for this, related to both the application and to features of ceramic armor. These factors relate primarily to cost, brittleness, field durability and repairability. Cost is high, as discussed below. The brittle nature of ceramics demands that they must be divided into small blocks or tiles to confine the damage on ballistic impact, and thereby achieve the required

multi-hit capability. Likewise, if exposed on the exterior of a ground vehicle, they are susceptible to damage by tree branches, dropped tools, etc. Dividing the ceramic into small units, however, introduces joints which can be a point of ballistic weakness. Furthermore, ceramic armor must have an outer protective cover (preferably metal and rubber) for the reasons stated above and to provide protection from low order ballistic threats. Unlike metals which can be welded for repair, ceramics must be replaced if damaged. The laboratories at Watertown have been aware of these features and have conducted programs to address the problems.

Cost is a major factor. In the 1970s, the cost of the best armor ceramics was over \$200 per pound. In aircraft where weight is at a premium, and the life cycle operational cost of extra pounds in an aircraft is on the order of hundreds of dollars per extra pound, the higher cost of an advanced material is much less of a disincentive. By contrast, with the exception of a few items such as components in gun sights and gas turbine engines, the average per pound cost of a combat vehicle is only a few dollars so that the high armor costs are generally not acceptable.

The high cost of armor ceramics is based on a series of factors, including: the base cost of the ceramic powder, powder consolidation costs, close tolerances on the ceramic blocks or tiles used in the armor systems, and the actual or projected production volume. Watertown addressed many of these factors in the early eighties. As a result, the price of many armor ceramics for Army development programs dropped by a factor of about five. Several Watertown researchers were recognized for this accomplishment by an Army R&D Achievement Award in 1987.

The application of ceramic armor to combat vehicles also differs from aircraft in the nature of the threat. The primary threat to aircraft is small arms, 0.30 caliber and 0.50 caliber armor piercing (AP), and 23 mm HEI ammunition. All are short length to diameter bullets (the AP rounds have a hardened steel core, and the HEI round is a small explosive shell) which impart an intense but short microsecond duration impulse to the armor. Although the ceramic is fractured by the impulse, the bullet is sufficiently degraded by the ceramic that the back up component to the ceramic (light weight metal or composite) can "catch" the foreshortened and fragmented bullet.

Although small and medium caliber bullets and shell fragments are a threat to combat vehicles, and may be the primary threat for light vehicles, the major threats to heavy vehicles

are long rod penetrators and the jet from shaped-charges.* These threats subject the ceramic to a longer, more-sustained impulse than conventional bullets. They tend to erode long narrow tunnels. Against these threats, brittle ceramics are prone to fail prematurely.**

Indeed, the expected efficiencies of ceramic armors against these threats, although very good, did not come up to levels that would be expected based on their performance against small (L/D) bullets, and not to levels high enough to overcome the cost and other disincentives associated with ceramics for combat vehicles. This was one of the principal findings of the AMC/DARPA Armor Anti-Armor and subsequent Ceramic Composite Armor (CCA) programs carried out in the late 1970s and early 1980s. This program involved Watertown and the Ballistic Research Laboratory (BRL) at the Aberdeen Proving Grounds, along with industry and the Department of Energy Weapons Laboratories. First BRL and then Watertown led those programs for AMC.

Army researchers attempted to address this problem by demonstrating the payoff of ceramics in a passive armor system. Between 1986 and 1988 with funding by the Abrams Tank Program Manager's Office, Watertown developed an armor materials system which combined ceramics, glasses and other non-metallics in a unique configuration for roof armor as part of the Block II Enhanced Survivability Program. This roof armor defeated the specified overhead threats within the space-weight envelope specified by the PM's Office, and provided even greater protection than originally expected against a mix of munition threats.

Also with both in-house and Tank Automotive Command R&D funds, Watertown, in cooperation with the Ballistic Research Laboratory (BRL), developed in the 1988 to 1991 time frame a tandem ceramic armor (TCA) system utilizing ceramics, metals and polymeric materials. This system more fully exploits the intrinsic armor capabilities of ceramics by avoiding the premature failure. The system was tested at subscale at Watertown, and at full scale at BRL and resulted in a 33% improvement over existing passive ceramic armors against a full-scale kinetic energy threat. A patent on this development was accepted by the U.S. Patent Office in 1995, and will be issued in the future when details are no longer classified.

In another demonstration of the potential of ceramic armor

* Bullets or penetrators are "Kinetic energy" threats: i.e., they have only the energy associated with their mass and velocity. They are classified as long rods if their length to diameter (L/D) ratio exceeds 10. Shaped charges are "Chemical energy" threats. They contain a metal liner with high explosive behind it, which converts the liner into a compact train of very high velocity particles with high penetration capability.

** This was clearly shown by researchers at BRL in the late 1980s.

in combat vehicles, Watertown used ceramic armor in the design of the Composite Infantry Fighting Vehicle demonstrator (see Structural Composite Armors). The use of ceramics, rather than the spaced steel armor used in the Bradley Fighting Vehicle, contributed strongly to the weight savings demonstrated by the CIFV.

Another factor delaying progress was the lack of a test to provide adequate evaluation and qualification of armor ceramics. A large data base of terminal ballistic data emerged from the AMC/DARPA Armor Anti-Armor and subsequent Ceramic Composite Armor (CCA) programs. Despite this extensive data base, limitations existed in comparing and interpreting the ballistic performance of the ceramic component. The problems of comparing systems containing variable (and often low) proportions of ceramic were compounded by use of different rear component materials, and variations in the test setup and projectiles used at the different test facilities.

In 1988, investigators at Watertown began developing a new test methodology intended to minimize or eliminate these factors, and to make evaluation and comparison of ceramic materials readily possible. This method became known as the "residual penetration" ballistic test, or "DOP" test. The conditions assumed by this test are that the impacting projectile is an erosively penetrating, heavy alloy long rod, and that the target backing plate is sufficiently thick and rigid to provide sufficient support for the ceramic and to prevent bending prior to projectile contact with it. The objective of the test is the construction of a performance map for ceramic materials over a range of areal densities. Performance is measured by the depth of residual penetration by a tungsten heavy alloy long rod penetrator into a semi-infinite steel backplate after passing through a ceramic target. For convenience, this value is often referred to as "DOP," for depth of (residual) penetration." Material comparisons may be made between selected baseline materials, for which performance maps have been developed, and candidate materials tested at any single areal density.

Related approaches had been taken by investigators at Rafael, in Israel, for determining efficiency of applique armors, and by Rafael and the University of Dayton Research Institute (UDRI) to provide a measure of ceramic performance against small arms projectiles. However, the effort at Watertown was performed independently, with the goal of addressing ceramic performance in medium and heavy armors rather than against small arms.

At the Fifth TACOM Armor Coordinating Conference in 1989, Watertown researchers first reported on the use of this test methodology. After this time, residual penetration ballistic testing rapidly gained acceptance within the armor community, with related work being performed by BRL, Los Alamos and Lawrence Livermore National Laboratories, Southwest Research Institute, UDRI, and many others. A conference, which was attended by researchers from all these organizations, was held at UDRI in April 1989 in an attempt to standardize the test methodology.

This early effort was not conclusive, but nonetheless evidenced the interest in obtaining a general test method for ceramics.

In 1990, Watertown implementation of residual penetration testing was adopted as the standard screening test for ceramics against kinetic energy (KE) projectiles by both BRL and Watertown. Subsequent to that time, Watertown has continued to expand its substantial database of ceramic performance information for comparative ranking of improved or novel ceramic materials, as well as for parametric analysis of ballistic performance variations resulting from material properties, cell size, confinement, and similar factors. By June 1993, the Watertown residual penetration test became formalized as MIL-STD-376. The ultimate goal continues to be making high-efficiency ceramic armor systems a more viable option, by facilitating interactions between government and industry toward the development and evaluation of improved ceramic materials at lower costs.

Thus, Watertown made many substantial contributions toward resolving problems associated with the use of ceramic armor on ground combat vehicles, and demonstrated the potential payoff from their use. Where and when they will be used in combat vehicles really depends on complex systems tradeoffs between ceramics and other competitive armor technologies.

Fiber-Based Armor Materials

Introduction

Fibers are an extremely important class of armor materials. It is evident that they are critical to composite materials, especially resin matrix composites in which they are the principal source of strength. Fibers are also used in the form of unbonded woven fabric in armors to defeat soft projectiles and fragments. The principal fibers used in armors are nylon and E-glass which were developed in the 1930s, S-2 glass and Kevlar in the late 1960s, and Spectra in the mid-1970s. Watertown played a major role in applying S-2 glass, Kevlar and Spectra to Army systems.

The desirable properties in a fiber for armor application are: high strength, high modulus, low density, low denier (small fiber diameter), and high elongation before fracture. The organic fibers are equally effective as fabric armors or as fabric laminates bonded with ductile resins. Glass fiber, the only non-organic fiber so far found useful in armor, is effective only when combined with a resin to form a composite. The first glass reinforced composite to find armor applications was Doron, named for General Georges Doriot of the Quartermaster Corps. It was used from World War II through the Vietnam Conflict in Marine Corps vests which incorporated Doron plates in pockets in a nylon

vest.

Much of the early work on this class of armor materials was carried out by the Quartermaster Corps and by the Navy. Watertown became involved in mid-1943 as a result of a high priority procurement of aircrew body armor for the Army's Eighth Air Force bombing of German occupied Europe from England.

Studies had shown that 21% of the wounds to Eighth Air Force bomber crews were from low velocity missiles. England had demonstrated the combat effectiveness of an experimental body armor consisting of overlapping plates of Hadfield manganese steel sewed in pockets of light fabric backed by canvas. On July 6, 1943, the Ordnance Department was tasked to procure over 25,000 body armor sets, with 25% of that quantity to be delivered to the Port of Newark by August 5. That requirement was met. Watertown's initial task was specification of the steel for the inserts. On July 10, Watertown gave its recommendations on steel chemistry, gauge, surface condition, heat treatment, physical properties and ballistic characteristics.

After furnishing the Eighth Air Force with the initial armor sets, the Army Air Force and the Ordnance Department turned to the question of improving the armor. Watertown was requested to undertake a program to devise a test method for production body armor.

As a result of this tasking, Watertown developed the first fragment simulators (see The Early Years) and carried out extensive tests on fabrics, including various weaves of nylon, fiber glass, and cotton; and plastic laminates, including Doron. The conclusions drawn from these tests regarding fabric and laminate armors are still valid today:

However, the resistance of a fabric depends, to a great extent, upon its ability to yield at the point of impact under the initial contact of the projectile, gradually increasing its resistance as it calls into play, centrifugally, the tensile strength of the threads. This necessitates clearance between the surface of impact and the surface of the target to be protected. In the practical application of a protective material to body armor this clearance may not be feasible. [Plastic laminates] characteristically cause the impacting projectile to expend a great deal of its energy in delaminating the adherent surfaces.

As will be seen in following sections, Watertown's contributions in the area of fiber-based armors are numerous. They include working with DuPont to demonstrate the potential of Kevlar as an armor material and applying Kevlar to personnel armor, spall liners, laminated metal-composite armors, and ballistic blankets. Watertown also applied Spectra fibers to personnel armor, and glass fibers to structural composite armor for combat vehicle hulls and turrets.

Personnel Armor for Ground Troops

In the late 1960s and early 1970s, studies of casualties in Korea and Vietnam showed that most were due to shell fragments. These studies also demonstrated that the then current personnel armor system was effective in reducing such casualties when used. That system consisted of a steel helmet with a separate molded resin-bonded nylon composite liner, and an unbonded ballistic nylon (high strength) fabric vest.

Based on these studies, a program was established to develop an advanced Personnel Armor System for Ground Troops (PASGT). The lead was with the Natick Laboratories (now the Soldier Systems Command). Natick, a former Quartermaster Corps Laboratory, has systems responsibility for food, clothing, protective equipment (armor and chemical protection), tentage, combat shelters, and air lift and air drop systems. AMMRC was funded by Natick to develop the lightweight armor materials systems for the PASGT. Natick, in turn, incorporated these materials into an improved PASGT system, taking into account factors such as comfort and vulnerability, as both are affected by configuration.

At Watertown, a series of high-strength, lightweight materials were investigated, including titanium, high-strength steels and various composites and plastics. Because of their superior ballistic performance, emphasis was given to the new polymeric and composite materials, specifically, high tenacity nylon, Kevlar aramid, stretched polypropylene and glass fiber composites (LMLD, low moduled-low density glass fiber). The final choice was Kevlar, a fiber originally developed by DuPont as a high-strength tire cord material.

When AMMRC scientists and engineers found out about Kevlar's properties, they recognized its potential as an armor material. This was based on earlier ballistic studies with nylon and with glass reinforced plastics. Kevlar was much stronger than nylon with approximately the same density (therefore, it had a higher specific strength) and had good elongation to failure. Earlier studies at Watertown had shown that these particular fiber properties should yield not only a superior fabric armor, but also a superior resin-bonded composite armor. AMMRC worked with DuPont on developing fabric weaves, fiber finishes and resin systems to demonstrate this potential. The first Kevlar composite panels were ballistically tested at AMMRC in the period 1971-1972.

Natick and AMMRC worked with the Vulnerability Division at the Ballistic Laboratory to assess the potential casualty reduction which would accrue from the improved ballistic properties. The results showed the potential for a 25% reduction in casualties at the same weight.

The next question concerned the processability of Kevlar. Could it be molded into a helmet? AMMRC used existing dies supplied by Natick for the old steel pot helmet to mold prototype

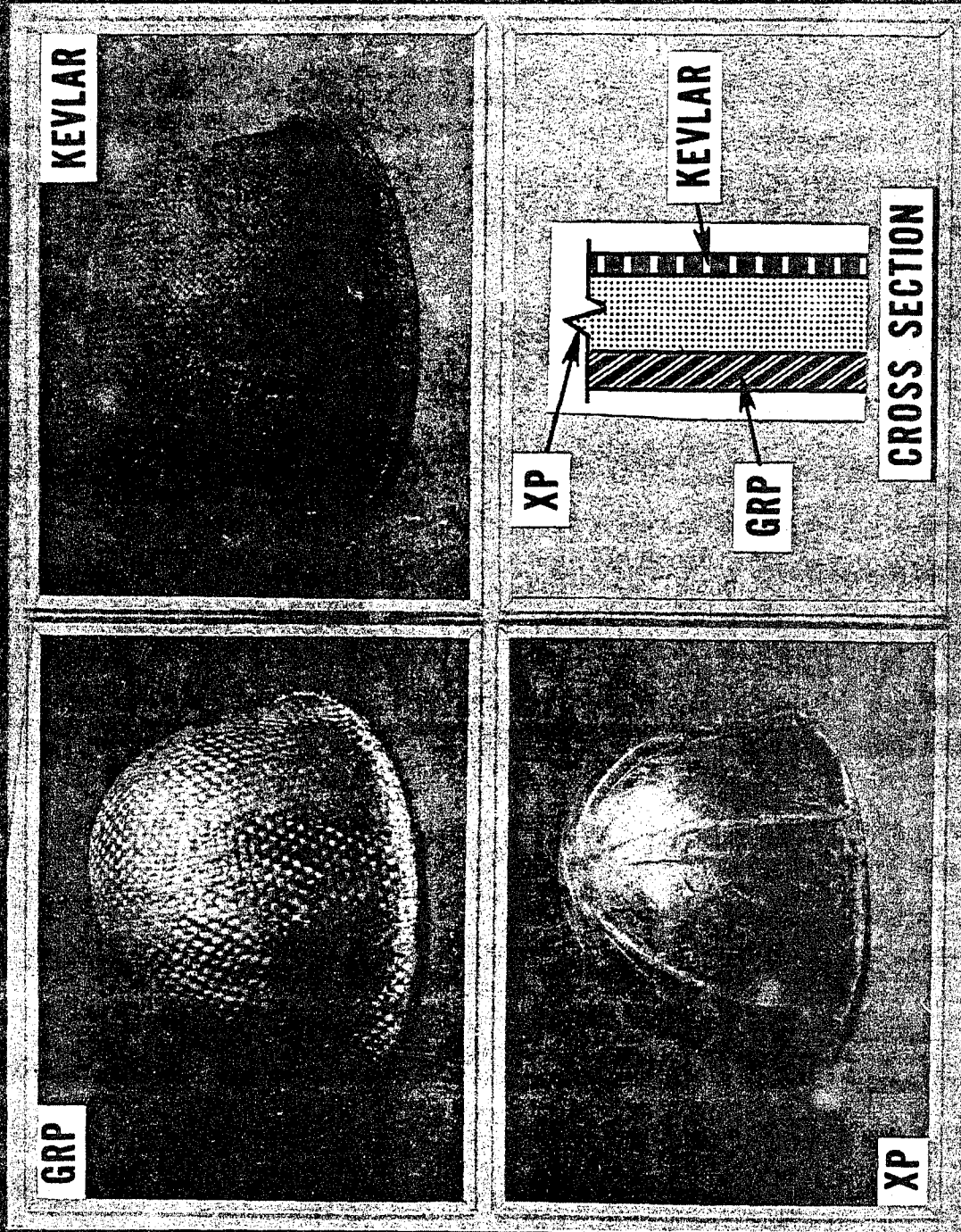
Kevlar helmets. A 50% thermosetting phenolic and 50% thermoplastic polyvinyl butylral (PVB) resin system was determined to possess the desired properties to achieve an optimal helmet construction. This resin allows molding at reasonable temperature (330°F), cures to a rigid-structural laminate and maintains the ballistic performance of the Kevlar material. Twelve Kevlar helmets were produced and ballistically tested to demonstrate processability and retention of ballistic performance.

To extract the maximum payoff from the new material, Natick developed the current helmet configuration with its low center of gravity and more extensive coverage of the head, ears and temple areas. This lower center of gravity, an improved suspension system and the fact that it was one integral unit rather than the two-unit steel and nylon, made the Kevlar helmet feel lighter on the head, while improving protection by 25%.

The development of the Kevlar vest was much more straight forward, since it employed basically the same multi-layer fabric approach as the nylon vest, but with the improved ballistics intrinsic in the Kevlar. The new Kevlar helmet and vest was fielded in the late 1970s.

After development of the PASGT Helmet and Vest, Watertown and Natick continued to work together on a series of improvements for personnel armor. In 1979 and 1980, a concern developed relevant to Soviet flechette munitions, which the U.S. also fielded (the "Beehive" round). These munitions contain thousands of small finned darts (flechettes), similar to a nail with fins to provide orientation at impact. Conventional unbonded fabric vests are effective against blunt objects such as fragments and soft bullets (which flatten on impact) by absorbing the projectile's energy across many fibers. The sharp, slender flechettes, however, slip between the fibers and readily penetrate many layers of fabric. The solution provided by Watertown in 1982 was a thin (0.050 inch) high strength titanium alloy (5Al-2.5Sn) sheet appliqued on the Kevlar fabric or laminate. The titanium component blunted the flechette, allowing the Kevlar to defeat the flechette. Natick demonstrated it in a prototype vest component with the titanium sheet in the form of small squares or hexagons to achieve reasonable flexibility. Production was not initiated as concern with flechette threats lessened, but the technology is on the shelf.

In the mid 1980s, Allied Signal brought out a new high strength fiber, called Spectra, produced by stretching polyethylene during processing to orient the polymer chain. Since polyethylene has a lower density than the polyaramids (Kevlar), the Spectra fiber looked promising as a lighter weight helmet material. Watertown undertook a program to develop fiber finishes and resins to incorporate the Spectra fibers in a composite. Stringent process controls were necessary, since the Spectra fiber could not be heated above 160°F during molding without its losing strength due to relaxation of the highly oriented molecular structure. Nevertheless, composites were



COMPOSITE GRP / XP / KEVLAR HELMET

Experimental helmets fabricated at Watertown for ballistic testing. The first Kevlar helmets (see upper right) were made at Watertown.

successfully produced which were 25% better than the conventional Kevlar in the fielded PASGT system. To demonstrate processability, several prototype helmets were produced and tested. These were 20% lighter than the PASGT helmet. DuPont responded, based on Watertown researchers' recommendations, by developing an enhanced Kevlar fiber (KM2) with higher elongation than the conventional Kevlar 29 fiber. Further, this new fiber was employed as a finer fiber (low denier) to achieve lighter weight fabrics (7 ounces/yd² relative to the conventional 14 ounces/yd²) for both helmet and vest applications. Watertown researchers had previously demonstrated that finer fibers in lightweight fabrics improve ballistic performance because the projectile engages more fibers during the penetration process. The KM2 fiber provided the same weight saving with less stringent processing requirements. It is now being introduced into the field as a lighter-weight helmet and vest system. This illustrates one of the more important functions of an Army Laboratory, which is not only to be aware of the latest technology which can be applied to Army systems, but also to guide the R&D and to stir the competitive juices of industry.

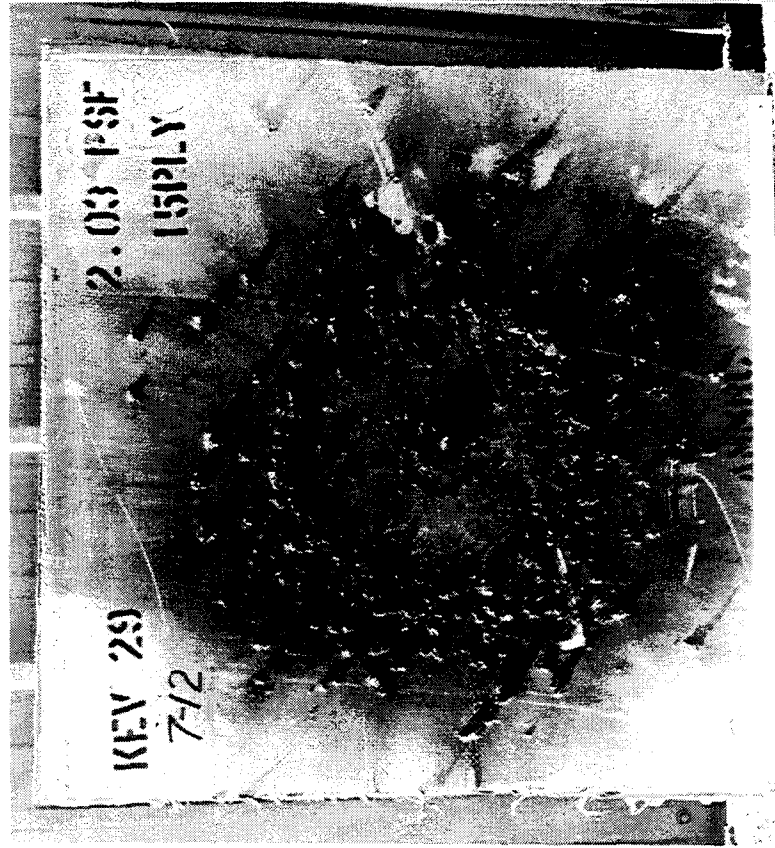
More recent research has focused on ceramics to provide protection from small arms fire in addition to fragments, because of the sniper threat to peace keeping and other operational forces. As noted earlier under Aircrew Protection, one piece curved ceramic-armor breast plates were developed during the 1960s to protect helicopter door gunners. They were made from boron carbide (one of the lightest but most expensive armor ceramics) backed by GRP (Kevlar was not available then). The current program is directed at employing advanced, lower-cost ceramic in multiple small tiles with Kevlar backups.

Before closing the section on personnel armor, it should be noted that the Vietnam era breast plates are still in stock after 25 years. During the peace keeping effort in Somalia, Natick had 200 of these breast plates shipped to Watertown. The purpose was to select 60 for shipment to Somalia, based on X-ray inspection for damage/defects, coupled with ballistic evaluation of typical faulty areas. This was accomplished in only seven days, with five Watertown personnel being commended for their efforts.

Spall Liners

In the 1972-73 time frame, it became evident that due to rapid advancements in weapons technology, Army Combat Vehicles were highly vulnerable to spall from battlefield weapons of higher order than those against which the vehicles were designed to protect. As the result of a directive, AMMRC began to look at how the survivability of the M113 family of armored personnel carriers could be improved. Although the armor exhibited desirable fragment-defeating properties, the Vietnam War and

KEVLAR LINER AT 16" BEHIND 1 $\frac{3}{4}$ " ALUMINUM (3.2" HEAT PENETRATION AT 0°)



FRONT



REAR

Compare the number of spall fragments impacting the front face of the spall liner with the lack of penetration on the rear face.

Laminated Metal-Composite Armor

Another area in which Watertown made a major contribution to armor materials technology is in the development of laminated metal-composite armor materials systems. Metals are good armor materials for the defeat of kinetic energy projectiles, both bullets and long rod penetrators. They are low cost; readily fabricated into structures by welding or casting; damage resistant (damage usually limited to the bullet hole); and readily repairable by welding. Their resistance to ballistic penetration increases linearly with strength as measured by either yield strength, tensile strength or hardness. Their drawbacks are a higher density on average than organic matrix composites or ceramics, and development of certain failure modes at higher strength levels which cause a fall off from the linear increase with strength. These failure modes are cracking, and plugging due to adiabatic shear (see Adiabatic Shear Deformation). In addition, metals spall during penetration by overmatching threats, especially shaped charge jets. This latter weakness was addressed by Watertown through the development of spall liner technology (see Spall Liners) for metal-hulled combat vehicles, and by the development of organic matrix composite hull technology (see Composite Structural Armors). The former weaknesses, i.e., failure by plugging or cracking was addressed by Watertown through the development of laminated metal-composite armors during the late 1970s.

In these armor materials systems, a metal front plate, e.g. aluminum or very hard steels (hardness above RC 50) is backed by a fiber reinforced organic matrix composite. Various composite backups were studied with fiber reinforcements of high strength nylon, glass and Kevlar. Because of Kevlar's superior ballistic performance versus fragment penetration, it emerged as the optimal backup component to metallic frontal plates. The Kevlar composite supports the metal and suppresses the initiation of petalling, shear plugging and cracking. These laminated materials systems are essentially a dual-hard (see Dual Hardness Steel Armor) type of armor. The aluminum Kevlar laminates provide enhanced fragment protection and the steel-Kevlar laminates superior protection against both armor piercing small arms projectiles and fragments.

These laminated metal composite armor systems have been fielded in the TOW Launcher on the Improved TOW Vehicle (1978); the Blackhawk Crew Seat (1980); the M-9 Armored Combat Earth Mover (1983); and the M-109 Self propelled Howitzer upgrade (1985). A number of Watertown personnel received an Army R&D Award for this development in 1983. Currently, extension of this technology to titanium is under investigation.

Ballistic Blankets

During typical battlefield scenarios U.S. Army and Marine Corps equipment and personnel are exposed to counter-battery fire from enemy fragmentation munitions. Ammunition depots, mobile radar installations, supply vehicles and personnel are vulnerable to fragments and blast effects, creating the potential for secondary explosions, casualties and equipment damage. In fact, fragments from artillery and rockets account for approximately 50% of all combat deaths and 63% of nonfatal wounds to U.S. troops. Because of their inherent flexibility, multi-functionality and fire-retardation characteristics fabric armor systems are the most effective means of enhancing ballistic protection.

Beginning in fiscal year 1990, the U.S. Marine Corps Research, Development, and Acquisitions Command initiated a program for the development of protective ballistic covers. Responsibility for providing technical expertise and recommendations on armor materials was in turn delegated to MTL. The technology of utilizing ballistic fabrics for the defeat of fragments was already available for fragmentation vests. The Ballistic Protection System extended that basic technology to protective covers, through ballistic characterization of high performance armor materials, including Kevlar, Spectra, nylon and polyester fabrics of various weaves. A mathematical model based on V_{50} ballistic limit values was developed for each material, thereby achieving prediction of fabric performance for various fragmentation munitions. The technology thrust was the evaluation and correlation of material ballistic performance threat analysis and fragment distribution as related to specific equipment under consideration.

In early 1993 Watertown developed demonstration prototype Kevlar blankets which consisted of modular interlocking panels which had an outer shell of camouflage patterned fabric and an inner layer of ballistic fragmentation protection. They are designed to attach to each other to provide protection over larger areas, and/or to provide additional thicknesses. Although the level of protection varies, depending on a number of parameters, a rough estimate of their protective capability is about a 25% reduction in casualties per blanket thickness for lower level fragmenting munitions such as hand grenades and small caliber mortars. Protection against higher level threats requires additional blankets, for example, versus the Soviet 152mm HE shell 12 blankets will achieve a 95% casualty reduction. In late 1993 the technology, data and prototypes were transferred to Natick Research Development and Engineering Center.

Prototype ballistic blankets have been fielded by the 1st Armored Division in Macedonia and by troops deployed to Somalia for Operation Restore Hope. Based on the quantity of different inquiries, the BOPS will be a multi-use technology to include:

protection for equipment, supplies, ammunition, petroleum, weapons system components, vehicles, shelters, and most importantly, personnel.

Structural Composite Armors

Introduction

Composites are combinations of two or more materials, which form a singular two-phase material whose properties are better than its individual components. The history of composite materials stretches from the ancient use of clay and straw bricks to today's commonly utilized fiberglass.

The introduction of very high-strength low-density materials as reinforcements and versatile matrix materials created a modern "advanced" class of composite materials. Classification of advanced composites yields four distinct groups: fibrous, particulate, hybrids and laminated. Fibrous composites consist of continuous or chopped fibers in a matrix. Matrices are binder materials whose purpose is to support, protect and transfer stress in the composite. Frequently used matrices include: metals, ceramics and polymers (epoxies, polyimides, thermoplastics and rubbers). The second type of advanced composite, particulate, is made up of particles in a matrix. Hybrids combine more than one kind of fiber matrix material system in such a way as to optimize the properties of the individual systems in the composite. When layers of various materials are bonded to each other in orientations to maximize the properties of the total composite the resulting material is classified as a laminate.

Advanced composite materials offer potential advantages over monolithic materials primarily in terms of high strength-to-weight ratio and stiffness. Other advantages may include: excellent resistance to ballistic penetration, wear resistance, near-net shape fabrication, fatigue life, temperature-dependent behavior, thermal and acoustical insulation and thermal conductivity. Possible problem areas encountered in the use of composite materials include: anisotropy, chemical instability, moisture degradation, dissimilar material corrosion, thermal stability, abrasion, impact damage, joining and cost.

The use of composites in military applications as a means of decreasing weight has been under study for some time. The U.S. Army has explored the application of composites to personnel armor, aircraft, combat and tactical vehicles and armaments. Fiber reinforced composite materials are also being used by the Air Force and Navy for aircraft and numerous ship and submarine applications. Many military technological advances in the field of composites are also finding extensive applications in the aerospace, automobile and other industries.

The following section examines Watertown's involvement in the application of composites to combat vehicles. Structural armor applications in terms of the composite turret and hull programs are addressed as well as the use of composites in creating blast-resistant vehicular components. Lastly, Watertown investigations into the fire resistance and combustion behavior of structural organic materials, e.g., composites and resins, are summarized.

Composite Structural Armor Research and Development for Combat Vehicle Applications

The research thrust in composite structural armor started at Watertown in 1981. The goal was to provide the Army with alternative materials to fabricate armored vehicle hull and turret structures. Fiber reinforced, organic matrix composites could offer vehicle weight reduction and survivability enhancement compared to conventional steel and aluminum systems. Commercially available composite armors of that time had good ballistic performance but low flexural strength and stiffness (modulus). They also suffered from moisture pickup problems that could further reduce mechanical and ballistic performance. Preliminary in-house investigations were conducted with a variety of fibers reinforcements, fiber finishes and resin matrix systems. E Glass, Kevlar 29 and Kevlar 49 fabrics were combined with epoxy, polyester and vinyl ester resin systems using the hand layup processing method. The objective of this investigation was to identify a combination of fiber, finish and resin that offered the optimum combination of mechanical and ballistic properties. Both thick and thin specimens, ranging from 8 to 42 plies were fabricated for mechanical and ballistic property testing.

During the program's 15 years, composite structural armor went from laboratory specimens, to composite hatches, to composite turrets, and ultimately, to the demonstration of an operational Composite Infantry Fighting Vehicle (CIFV). Based on the success of the Watertown work, the technology was transitioned to the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) for further development. The U.S. Marine Corps also supported early developments by Watertown in composite hull technology.

Composite Hatch Doors: The first contractual effort involving a vehicle component was the Lightweight Combat Vehicle Cargo Doors project that Watertown sponsored with Goodyear Aerospace. Two types of composite cargo doors for an amphibious landing craft were designed, fabricated and tested. The Type I doors were a hand layup E Glass/Polyester system, using 60 plies of fabric. The Type II doors were a combination of .22 inch thick, heat treated 4340 steel and 27 plies of resin transfer molded E Glass/Polyester. The all-composite system demonstrated fragment

protection, and the steel/composite system demonstrated combined armor piercing and fragment protection (see Metal-Composite Laminate Armors).

Prepreg Development: Other composite processing methods were being considered as alternatives to hand layup and resin transfer molding. The technical team recognized that component fabrication using preimpregnated fabric should be investigated. This approach led to a 1984 contractual effort entitled Prepreg Systems for Structural/Ballistic Laminates with Owens-Corning Fiberglass. It was at this time that the OCF S-2 Glass fiber was first woven into a ballistic fabric for Army evaluation. Possessing higher tensile strength than E Glass, S-2 Glass offered enhanced ballistic performance. This produced higher weight reduction possibilities compared to aluminum armor. The glass composite prepreg was moldable shortly after impregnation yet storable at room temperature for 30 days. The program also addressed multiple ply layup, automated laydown, cutting/trimming and vacuum bag molding for thick section parts.

Composite Turret: Based on the success of the in-house and contractor research, the technical team next wanted to apply the composite technology to a more complex armored vehicle component. Two new lighter class armored vehicles were considered: the Army/Marine Corps Armored Fighting Vehicle (AFV) and the Army M2 Bradley Fighting Vehicle (BFV). The AFV is a wheeled system having a highhard steel hull and turret, whereas the M2 BFV is a tracked aluminum hulled vehicle using thin steel spaced armor in selected areas. During that time frame the Army pulled out of the AFV program, leaving the Marine Corps to complete development. The M2 BFV turret was selected as the next demonstration component for composite structural armor technology. The lower level fragment/AP threat protection levels for the M2 were ideal for demonstrating the weight reduction possibilities of composites.

The complexity of the turret offered a solid challenge without the high technical risk of jumping directly into a hull development program. A multi-year composite turret program was also affordable under the 6.3 funding levels for FY84 to FY87. A contract for the design, fabrication and testing of a composite turret was awarded to FMC Corporation, the builder of the BFV, with Owens-Corning Fiberglass as a subcontractor. All of the ballistic design data needed by FMC was generated in-house at Watertown's ballistic ranges.

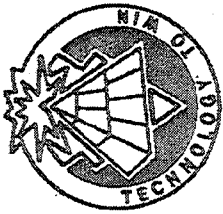
A hybrid M2 turret was designed with S-2 Glass/Polyester replacing the aluminum structure in the roof, rear and right side. Finite Element Analysis was performed and verified by structural and ballistic tests on critical areas and joints. Five hybrid turrets were fabricated during the program. One turret was subjected to static, modal and shaker testing, meeting all structural criteria. Ballistic testing of one turret showed six of eight turret facets exceeded BFV 14.5mm protection requirements. Design changes brought the other areas up to design levels. Two small ballistic test programs were conducted

and documented to evaluate spall reduction performance and the effects of reactive armor detonation. Findings indicated a clearly impressive reduction in spall when the composite material was used rather than a steel/aluminum system. This had some major implications in armor design. Watertown had previously developed Kevlar spall liners for aluminum combat vehicles to increase crew survivability (see Spall Liners). The results of these tests showed that these liners would not be necessary in composite constructed vehicle components. This would enable an even greater weight reduction in comparison to aluminum vehicles with spall liners.

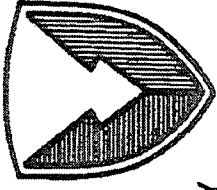
The turret manufacture proved straight forward and economically feasible, but further development in resin chemistry and cure process was required. One turret was fully outfitted and mounted on a BFV vehicle for field testing and gun firing tests. The turret was subjected to 1500 miles of durability testing over a variety of terrains at the FMC Camp Roberts' test course. Strain gage and accelerometer data showed measured loads below FEA predicted levels by approximately 20%. A series of special tests were conducted to determine interior noise, infra-red signature, sight alignment retention, time on target and rough terrain response and sight flutter. Durability field testing and special tests revealed that the hybrid composite turret met or exceeded BFV requirements. A 16.5% weight savings was realized in the areas where the aluminum was replaced with composite.

Composite Hull Program (CIFV and Heavy Composite Hull): The next logical step in the development and demonstration of composite structural armor technology was a vehicle hull structure. Watertown had the personnel and experience needed to plan and manage an R&D contract of this type. FMC Corporation had the experience with the composite turret and M2 BFV to be the prime contractor. The molding of such a large, complex, thick composite structure had never been accomplished and would be a milestone in composite processing technology. Designated as one of the Department of Army's Top-20 Technology Demonstration Programs, the hull program was leading the field of interest in composites for next generation armored vehicles. The composite hull program coupled in-house research with the three phase contact with FMC Corporation. Initially the contact planned for fabrication of two Composite Infantry Fighting Vehicles in Phase II and III. Based on the success of the Phase II CIFV, and changing Army requirements, Phase III was rescoped for design and testing of a 55 ton weight class hull structure.

During Phase I (1986-87) materials evaluation the ballistic performance, flammability characteristics (see Flammability Research), mechanical properties and processability of four S-2 Glass prepreg systems were examined. The process development work showed that a large hull structure could be molded using only vacuum bag pressure with reproducible and predictable quality. Ballistic testing in-house identified the most weight-efficient armor systems for both overhead and armor piercing

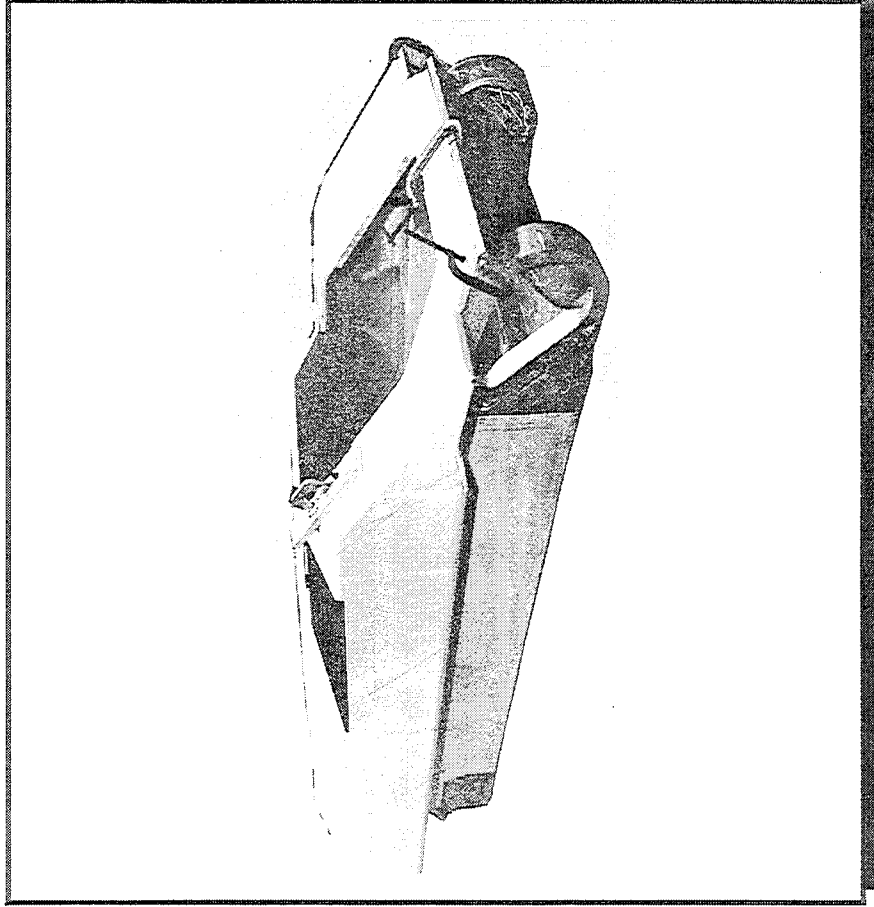


MATERIALS FOR LIGHTWEIGHT STRUCTURES
COMPOSITE ARMORED VEHICLE (CAV)
ADVANCED TECHNOLOGY TRANSITION DEMO (ATTD)

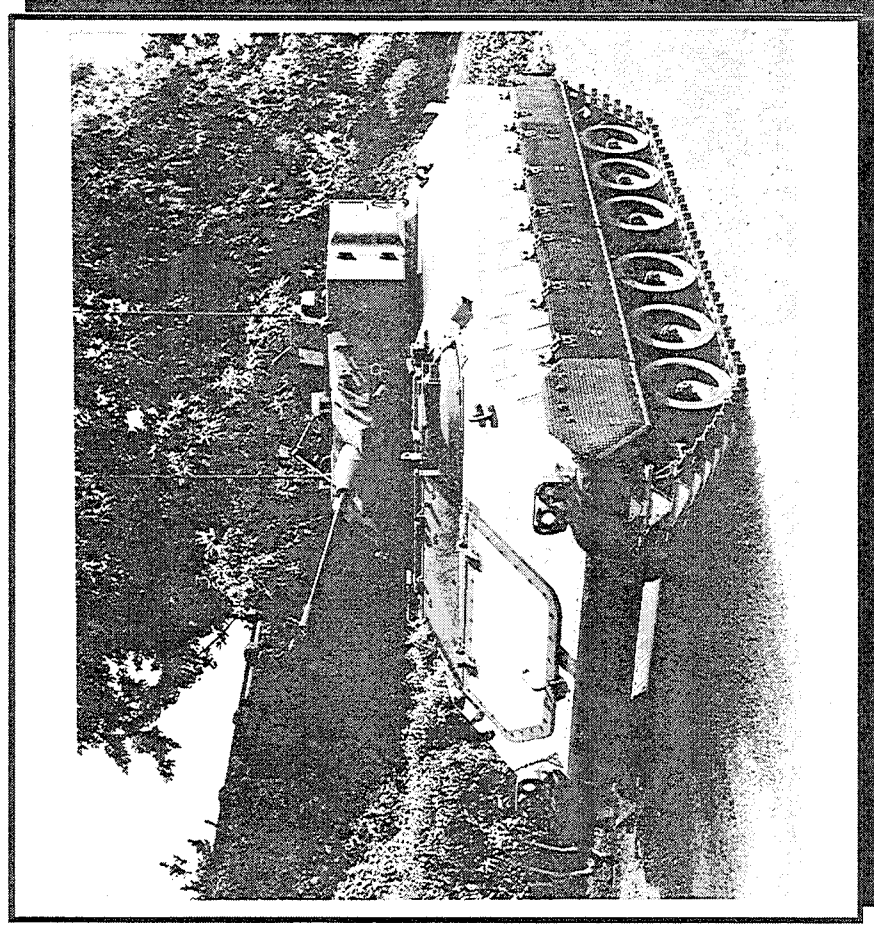


**US ARMY
LABORATORY COMMAND**

MATERIALS TECHNOLOGY LABORATORY



**S-2 BALLISTIC GLASS/EPOXY COMPOSITE
HULL TECH DEMO**



**FULLY OUTFITTED COMPOSITE HULL TECH
DEMO WITH BRADLEY COMPONENTS**

threats. Full scale structural and ballistic test specimens were fabricated and evaluated both in static and dynamic testing. Weight projections for the selected hull design predicted that the CIFV composite hull with ceramic and expanded metal armor could be 25% lighter than the M2 BFV aluminum hull with steel armor.

During Phase II the Composite Infantry Fighting Vehicle was designed, fabricated and subjected to a 6000 mile field durability test and special tests. Detailed manufacturing process procedures and quality assurance plans were developed and documented. The durability of the composite hull exceeded the expectations for reliability and overall performance. The predicted 25% weight reduction for hull structure and armor was achieved by substitution of composites and ceramics for aluminum and steel. Field test results validated both rigid body dynamic modeling and finite element analysis results. A major milestone was the CIFV Rollout Ceremony held on June 23, 1989 at FMC Corporation, San Jose, California. During that ceremony the CIFV was driven by General Louis Wagner, CG AMC. The CIFV was also displayed at the LABCOT Technology Show and in Washington, D.C. at the Annual AUSA Show.

Phase III addressed the development and demonstration of composite materials to heavy combat vehicle systems. The Army's Armored Systems Modernization program was geared toward future heavy systems in the 55 ton vehicle weight class. The Heavy Composite Hull was configured around both heavy tank armor space requirements and gun firing loads. The heavy hull had a composite top plate, sidewalls, belly plate and turret cylinder. Steel was used in the front nose, rear idler and lower hull areas. E Glass/Epoxy and S-2 Glass/Polyester systems were both used in the heavy hull structure. The E Glass/Epoxy was used in regions requiring higher axial compressive strength and not requiring as much ballistic performance. Structural testing included hull racking tests, side armor loading tests and a suspension housing attachment test. The Phase III effort was completed in December 1994. The Heavy Composite Hull also demonstrated a 25% weight reduction compared to an RHA steel hull for the same weight class of armored vehicle.

Technology Interaction and Transition: The composite hull program received considerable technical support from many other branches and divisions at Watertown. Research efforts in polymer characterization, flammability analysis, armor design, ceramic materials, signature reduction and machining methods are examples of such support. Another important aspect of this program was the importance of technical marketing of the technology. Over 80 formal presentations and papers were given on the composite hull program during the years 1985 to 1994. The technology was gradually understood and more accepted by the military because of the contract results and aggressive marketing approach. Based on the success of the Watertown Composite Hull Program, the Army has obligated over \$60 million to the Composite Armored Vehicle Advanced Technology Demonstrator (CAV-ATD) program being managed

by TARDEC.

Blast-Hardened Suspension Components for Tracked Combat Vehicles

In 1976 the Engineering R&D Command at Fort Belvoir, Virginia, invited AMMRC to participate in the development of a blast-resistant track for Engineer Corps vehicles. Track systems were susceptible to severe damage or severance by land mines with consequent loss of mobility, rendering the vehicle incapable of fulfilling its mission and liable to destruction by enemy fire. Mines as small as five pounds of explosive could incapacitate any tracked vehicle.

As a result of the Fort Belvoir invitation, from 1977 to 1980 AMMRC participated in an investigation regarding the feasibility of hardening the suspension components of tracked combat vehicles against landmine threats. The program was directed by the U.S. Army Mobility Equipment Research and Development Command (MERADCOM). Besides AMMRC, Army support was provided by the U.S. Army Tank-Automotive Research and Development Command (TARADCOM), the U.S. Army Materials Systems Analysis Agency (AMSAA) and the U.S. Army Ballistics Research Laboratory (BRL). The Martin-Marietta Corporation, Orlando Division, served as the contractor for this effort.

Roadwheels and track shoes were the principal suspension components being considered for blast hardening. During the program, some novel concepts were investigated, both in component design and in material selection. The resulting hardened prototypes incorporated elastomeric, plastic and composite materials in place of much of the conventionally-used steel, thus leading to some reduction in weight, as well as improvements in blast resistance.

Besides mine-blast survival, there was a need to generate information regarding the durability of these materials against mobility hazards. It was expected that mobility operation would lead to occurrence of fatigue, i.e., a progressive softening and weakening of the material, perhaps accompanied by growth of micro-fractures and/or by destructive hysteretic heating. The AMMRC effort was therefore aimed at: 1) reducing the hysteretic heating effect to avoid blowout and increasing the energy-absorbing characteristics of the polyurethane roadwheels through polymer selection and modification; and 2) developing test methods for selecting track shoe materials, having greater resistance to abrasion, penetration, cutting and chunking.

AMMRC performed several types of laboratory fatigue tests to screen a variety of materials for application in prototype hardened suspension components. The efforts were divided into two main categories, i.e., materials for roadwheel encapsulants and materials for track shoes.

Roadwheel Encapsulants: A roadwheel encapsulant must be formed in place from a liquid castable material that polymerizes into a

hard, tough elastomeric solid. Polyurethanes are a logical choice for this application. However, it is well known that polyurethanes are susceptible to heat buildup during cyclic or repetitive loading (as in wheel rotation), resulting from energy dissipation processes (hysteresis) occurring in the material during deformation. From contractor and AMMRC test results, AMMRC showed that the degree of internal temperature rise was least for those polyurethanes with the lowest values of the low-temperature transition and the highest values of the high-temperature transition, i.e., the polyurethanes having the most phase-segregated microstructures.

In later cyclic compressive tests of some simulated armored vehicle roadwheel cross sections, comprising fiberglass inserts and polyurethane encapsulants, AMMRC demonstrated that both lesser encapsulant thickness and greater encapsulant reinforcement produced a decrease in the internal temperature rise. To examine the behavior of the complete roadwheel, the contractor fabricated two M60 full-sized prototype roadwheels, weighing about 110 pounds each. In its large-scale mechanical testing laboratory, AMMRC subjected the roadwheels to non-rotational, non-translational cyclic compression against a prototype track shoe. The resulting wheel encapsulant relative internal temperature rises noted in these runs correlated with the previous small-scale fatigue tests and indicated the magnitude of hysteretic heating that might occur during sustained mobility operation.

Track Shoe Materials: Several types of materials were examined as candidates for a prototype track shoe. Thermoplastic molding materials were obtained from resin manufacturers and included nylons and polyesters, some reinforced by various fibers. Also, a sheet molding compound was obtained as a glass reinforced thermo-setting polyester in the form of compression molded panels.

AMMRC also devised tests to simulate some aspects of track shoe interaction with the terrain. These tests were intended to determine cutting resistance, indentation resistance, impact response and compressive fatigue resistance. In addition to these characterizations, standard test methods were employed to determine abrasion wear and the coefficient of friction (on concrete). The same tests were performed on the rubber materials of the track pads currently employed in order to provide a comparison.

As a result of AMMRC testing and design efforts, the blast resistance objective was achieved. Mobility was retained after the explosion of charges up to 21 pounds. The design that evolved had roadwheels riding U-shaped guides atop the track shoes. The metal components of the shoes and their linkages were of tough, hardened steel, and heavier than usual. Rubber bushings were not utilized. The track shoe bodies were molded of glass fiber reinforced polyester. Roadwheels were polyurethane cast around a metal hub and reinforced by five epoxy-fiberglass thick-walled hollow cylinders spaced between the hub and a

fiberglass-epoxy fabric reinforced rim. The omission of conventional spokes served to reduce energy transfer and damage to the hub and drive system. The unorthodox design produced an important consequence: the track system weighed 20% less than conventional track.

Test results indicated that "hard" materials are preferable to "soft" materials, except for abrasion wear and friction coefficient. Excessive wear occurred at the ground surface of the plastic track shoes and at the rim of the polyurethane roadwheels. It was concluded that modification of commercial plastics was necessary to overcome demonstrated performance deficiencies and that novel composite constructions might be required to achieve the optimum combination of properties needed for mobility operation. With hindsight and more than a decade later, it can be seen that rubber materials might have been a more durable choice for both track shoes and roadwheels. Longer wearing rubber compositions such as hydrogenated nitrile rubber are now available. Injection molding of rubber is now well developed and might be a suitable process of fabrication.

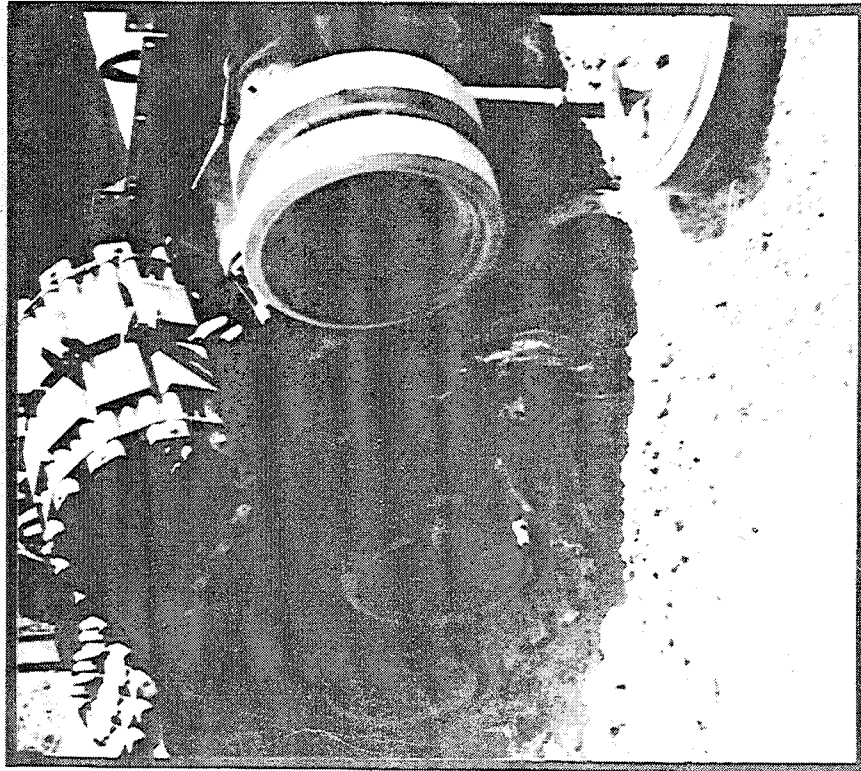
Other Activities: At intervals during this project, the contractor conducted small-scale blast tests upon prototype suspension components. As a major and critical demonstration, the contractor performed full-scale mine-blast tests upon tracked vehicles fitted with both the standard and the prototype suspension components. The latter utilized the best polyurethane for the roadwheel, and the sheet molding compound for the track shoe. Results from this test illustrated the superior blast resistance of the prototype suspension system, as manifested by less severe damage to the components and vehicles, as well as a decreased loss of vehicle mobility.

However, soon afterwards, due to changes in Army priorities, there was little funding available for follow-on work with blast-hardened suspension components. Aside from some further laboratory characterization of materials, the successors to AMMRC have not continued with this program. The need for blast-resistance in trucks and roadwheels will undoubtedly surface again. When it does the pioneering efforts of AMMRC in the 1970s will provide a basis for continued efforts towards the development of better materials and designs.

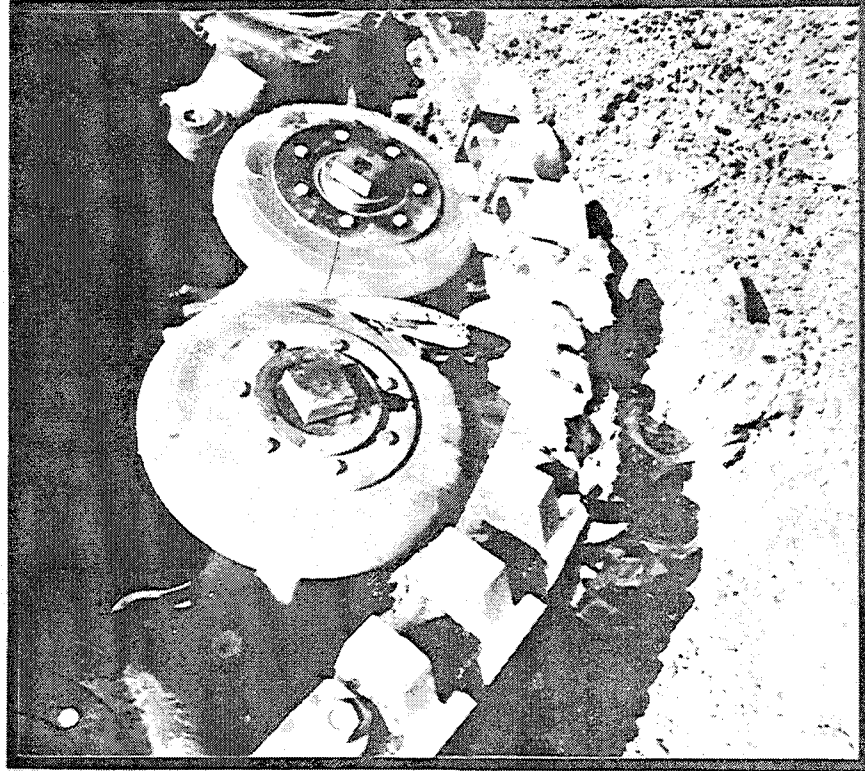
Composite Blast Resistant Armored Vehicle Floor Lightweight Hull Floor Program

The ability of a woven fabric composite laminate to withstand a blast load has been the subject of debate within the military engineering community. Many felt that the composite laminate would be easily ruptured by loads such as those produced by reactive armor detonation or mine blast. Composites engineers believed that the material's ability to absorb, dissipate and dampen out loads would make it superior to metals when compared

5 POUND BLAST COMPARISON



**CURRENT M60
SUSPENSION**



**PROTOTYPE COMPOSITE
SUSPENSION**

A 5 POUND CHARGE, WHICH DISABLED THE CURRENT SUSPENSION SYSTEM, CAUSED ONLY MINOR DAMAGE TO A PROTOTYPE SYSTEM. THREE FIBERGLASS SHOE BLOCKS WERE BLOWN OUT VENTING MOST OF THE BLAST ENERGY INTO THE AIR AND PREVENTING STRUCTURAL DAMAGE TO ANY OTHER VEHICLE COMPONENTS.

on an equal areal density (psf) basis.

In 1987, MTL ran a series of tests simulating the effect a reactive armor detonation would have on aluminum and composites. Thick section S-2 Glass composite specimens and structures were tested, using metallic flyer plates and actual reactive armor boxes. The composite showed the ability to resist explosive shock loads and failure during dynamic deflection. It exhibited high toughness compared to aluminum and steel, absorbing energy by delamination. The relative blast capacity was related to the material's strength, stiffness and density. The stiffness, in turn, was related to the specimen thickness, and the lower density composites are thicker than metals at equal areal density. As the result of FMC Corporation's request that a composite bottom plate be considered for the Composite Infantry Fighting Vehicle, simple blast tests using four square composite and aluminum specimens and C4 explosives at a six inch standoff were conducted. Results predicted that the S-2 Glass laminate had a blast impulse capacity twice that of equal weight aluminum. Based on that finding the CIFV has a composite belly plate.

Watertown researchers funded General Dynamics Land Systems (GDLS) to conduct additional blast testing. The contract was co-funded by the Marine Corps Program Office as the Marine Corps had a strong interest in composites for future amphibious landing craft bottom plate applications. A contract entitled "Lightweight Hull Floor Program" was awarded to GDLS in January 1992. Its objective was to develop a test method for screening materials against blast. The test fixture design geometry simulated the lower hull and floor plate of a future light armored vehicle. Equal weight (10 psf) aluminum and S-2 Glass laminates were compared, the laminates being resin transfer molded (RTM) by GDLS. The specimens were six foot square with a four foot square unsupported center area and were bolted to a reusable metal frame representing the lower vehicle chassis. This test used an eighteen inch standoff compared to the six inch standoff used by FMC. Five tests were performed on each material. Hemispherical C4 explosive charges ranging from four to sixteen pounds were detonated under the fixture.

Both the composite and aluminum resisted complete penetration with the composite having less permanent deformation, although the composite's transient deformation was considerably greater. Additional testing against mine threats having flyer plates or self forming penetrators was discussed but not conducted. It was felt that the composite would offer better performance against these types of threats. Based on this Watertown sponsored work, the Weapons Technology Directorate adapted the Watertown test method to evaluate composite sandwich core specimens. Further development for composite bottom plates is being conducted under the Army's Composite Armored Vehicle Advanced Technology Demonstrator (CAV-ATD) Program.

Flammability Research

The following section on Flammability Research was substantially written by Stanley Wentworth in tribute to the memory of the late Dominic Macaione, a member of the ARL/MD Polymer Research Branch and founder and lead scientist of Flammability Research activities. As such he was the principal Army spokesperson on flammability issues.

With the growing importance to the Army of organic materials such as resin matrix composites, it became evident that the flammability of such materials was an issue that had to be addressed. Composite systems consist of about 60 to 80% by weight of lightweight high strength-high modulus reinforcing fibers and about 20 to 40% by weight of specialty resin systems. Although composite systems are very serviceable, there is always a fire safety concern, as the resins generate heat and various combustion products as they burn. Generation of heat creates a thermal hazard, whereas generation of combustion products creates a nonthermal hazard due to toxic and corrosive environments with reduced visibility. It was soon recognized that flammability testing and assessment is a highly specialized field requiring a substantial commitment of resources, both in dollars and in personnel.

Beginning in the early 1970s, the Polymer Research Branch acquired the capability to conduct such testing. Gradually, the ability to perform thermogravimetric analysis, limiting oxygen index and temperature dependent limiting oxygen index determinations, smoke density measurements and effluent toxicity analysis was established. Each of these tests provides an insight into some aspect of the behavior of a material in a fire. For instance, thermogravimetric analysis indicates the basic thermal stability of a material while smoke density measurements suggest to what extent vision is impaired by the smoke generated by its burning, a very substantial issue with regard to an individual's ability to perform tasks near, or to escape from, a fire.

These capabilities were soon applied to flammability assessments of materials proposed for use in such diverse systems as the GUARDRAIL Tactical Shelter, the M-109/E4 Howitzer, thick section composite armor and APC spall liners. In the case of GUARDRAIL, these assessments prevented the selection of an especially flammable material, thereby contributing significantly to the fire safety of the structure.

Also, as part of the Branch's core program, the flammability characteristics of a variety of materials, both specific and generic, were determined and incorporated into a Flame Retardant Additives Data Base which was then available as a guide to those engaged in materials selection for systems in development.

Perhaps the most conspicuous utilization of these capabilities was its application to the evaluation of the flammability characteristics of materials under consideration for

use in the Army's armored vehicle composite hull program (see Composite Structural Armor Research and Development for Combat Vehicle Applications).

The Program Manager for the Bradley CIFV had expressed real concern that these resin matrix composites might be readily ignited when exposed to various battlefield threats, severely compromising the vehicle's survivability. The Branch's by now well developed expertise in flammability assessment was brought to bear on the problem. A series of tests, including the Propane Burner Fire Test, which was developed specifically for the screening of these thick section composites, was soon conducted. They demonstrated conclusively that properly formulated resins presented a minimal fire hazard. The fiber reinforced composite materials exhibited high resistance to ignition, a high heat of gasification and a low Fire Propagation Index (FPI), indicating that self-sustained fire propagation would be difficult. Thus assured, the Program Manager gave his blessing to the program's continuation. Had these concerns not been put to rest, it is likely that work on thick section composite armor would have ceased at this point. The Army would have been denied this innovative technology and one of the Directorate's most successful programs prematurely terminated.

Selection of "The Science and Technology of Fire Resistant Materials" as the topic of the 39th Sagamore Conference may be considered the capstone to the Materials Directorate's endeavors in the flammability area. This important conference, which each year focuses on a topic of current or emerging interest to the Materials Directorate (see Sagamore Conferences), was held in the late summer of 1992. Attended by many of the country's leading investigators in the field, the conference featured a series of papers on a broad spectrum of subjects, ranging from thermally resistant polymer science to fire theory to flammability testing. It was highlighted by a keynote speech by Professor Gordon L. Nelson, the nation's leading authority on materials flammability. The Proceedings volume, edited by Dominic P. Macaione, the Program Chairman, is a valuable reference for workers in the field.

Mr. Macaione's untimely death in 1993 has substantially curtailed the Directorate's activities in the flammability area. A significant program in support of Composite Armored Vehicle technology continues at this writing, however. It is a fitting memorial to Mr. Macaione and his untiring efforts to ensure that flammability assessment continues to receive proper attention by systems developers.

Steel Armor

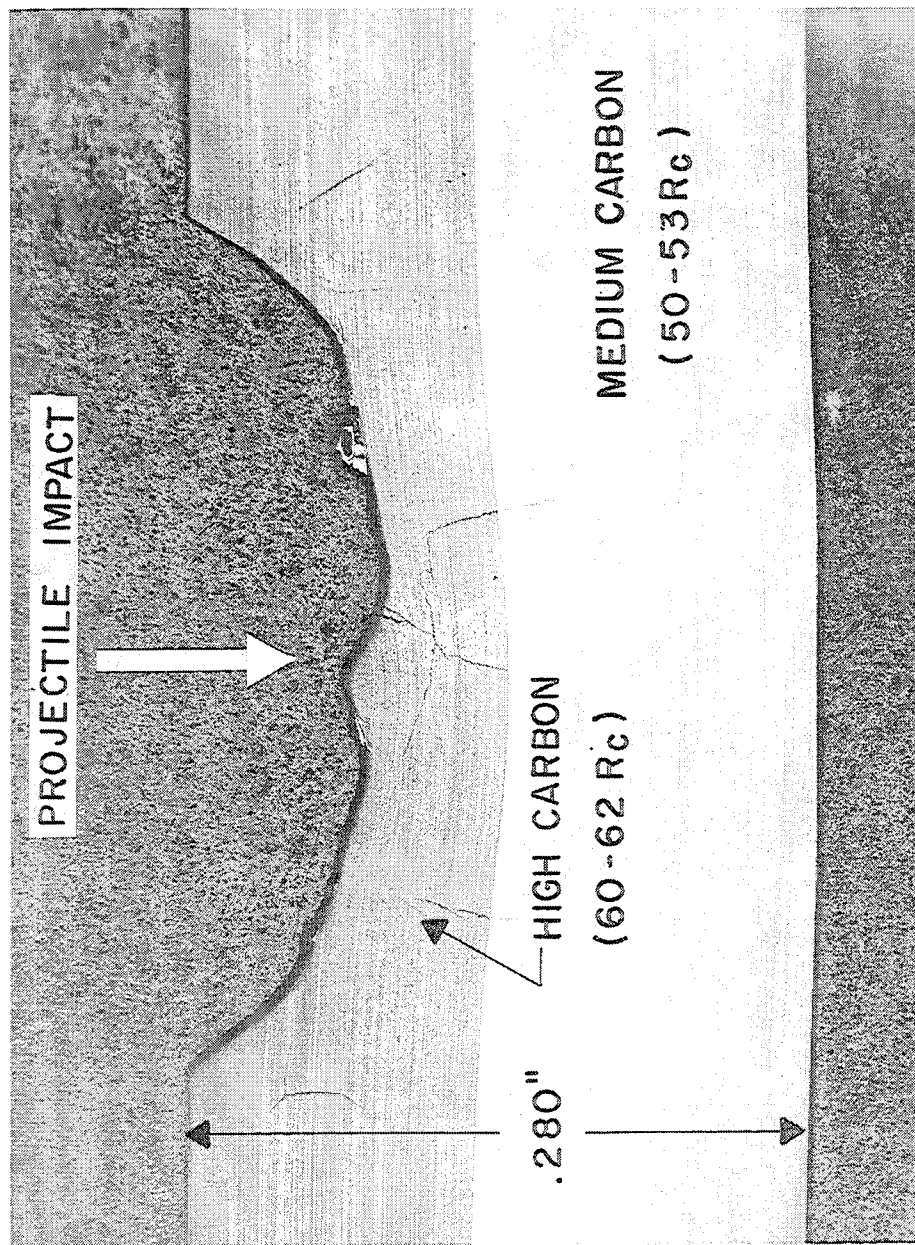
Dual Hardness Steel Armor

During a four year period in the early 1960s more technological advances in lightweight armor materials development were achieved than in all of history prior to that time. They were achieved primarily as a result of Research and Development conducted and/or sponsored by the Army Materials and Mechanics Research Center. Included in those technological breakthroughs was the development and commercial availability of dual hardness steel armor (see Ceramic Armor section on Aircraft/Crew Protection).

Experiments on-going at Watertown demonstrated and continuously verified the critical significance of strength in steel for effective and efficient defeat of small arms piercing (AP) projectiles which at that time were emerging as a formidable threat in the war in Southeast Asia. The very property that was proven to be absolutely necessary (high hardness) in armor steel was, ironically, the most problematic. As a stand-alone requirement, hardness in steels is easily achievable primarily by heat treating of high carbon steels. Routine quench and temper of high carbon steels result in plate hardness in the range of 600 HB (required as a minimum for resistance to penetration of AP projectiles). At this hardness level, plate fracture frequently occurs. This dilemma established and continues to present the greatest technological challenge to steel armor researchers, developers and producers. The research, development and production of dual hardness steel armor represents to this day the most significant achievement in meeting that technological challenge.

In order for a steel to be considered a major armor candidate for AP projectile defeat it must, at a minimum, be very hard. In addition to hardness, the steel armor must be capable of sustaining multiple projectile impacts within a specifically confined area of the plate. Also, spalling of the material especially in back of the plate, is unacceptable. As previously discussed, most monolithic steels fracture upon initial impact. As a result, limits on armor hardness had to be established to prevent shatter of the armor due to lack of toughness. In order to take advantage of the resistance to penetration associated with high hardness while circumventing the consequences of reduced toughness, the dual hardness laminate composite approach was conceived.

The first test plates of dual hardness steel armor were fabricated by and ballistically tested at Watertown in the early 1960s. Because of promising results Watertown funded a research program with Philco Corporation Aeroneutronic Division and Republic Steel Corporation in 1964. Alloy steels with different carbon levels were finished ground on their interfacing surfaces, and the outside edges of the mating plates were welded together. The welded packs were then metallurgically bonded by hot rolling. In addition to roll-bonding the (multiple) rolling cycles were also designed to thermal mechanically strengthen the pack. The contractual effort was a technical success and soon after, the armor was used where possible in Southeast Asia.



Transverse section through an impacted dual hardness steel armor plate. Note the cracks propagate only a short way into the tougher rear plate.

Due to the nature of the thermal mechanical strengthening or "ausforming" of this type of armor, appropriately designated Ausformed dual hardness armor, the armor was in the fully hardened condition upon leaving the rolling mill. Although there were benefits derived from Ausformed dual hardness armor, critical deficiencies quickly emerged. Secondary fabrication of Ausformed armor, including machining and forming, were difficult at best, thereby significantly limiting its use.

Concurrent to establishing the commercial availability of Ausformed dual hardness armor, research and development was being conducted at Watertown and U.S. Steel Corporation which demonstrated the feasibility of producing a dual hardness steel armor plate which could be successfully roll-bonded and rendered in the annealed condition after the rolling operation. In this type of dual hardness steel armor, the martensite transformation temperature of the front and back steels are adjusted to be similar to minimize distortion on quenching. The prospect of achieving a "heat treatable" variety of dual hardness steel armor with promise of much greater flexibility and applications resulted in a major contractual effort sponsored by AMMRC/AMRA, starting in 1967. The effort solicited armor test plates from several steel companies. The plates were to be fully bonded, heat treatable and after heat treating ballistically equivalent to the Ausformed variety. Of the several companies that participated in the contract, two companies, U.S. Steel Corporation and Jessop Steel Company successfully met the contract goals. U.S. Steel eventually made a Corporate decision not to market the product. Jessop Steel Company thus emerged as the sole producer and continues to this day as the country's only known producer of roll-bonded heat treatable dual hardness steel armor.

Applications of dual hardness steel armor include: combat vehicles, gun mounts, ground support equipment, critical aircraft components, executive limousines, etc.

Electroslag Remelted Steel Armor

The success of Roll-Bonded Dual Hardness Steel Armor is attributed to the fact that it provides AP protection at about 50% weight reduction as compared to conventional Rolled Homogenous Steel Armor. As previously discussed, this outstanding ballistic protection is possible because of its high hardness. Wider Army use of Dual Hardness Steel Armor has, nevertheless, been limited. The main reason for limited use has been the high cost associated with producing the armor and fabricating critical components.

These factors, as well as the general problems encountered with very hard steels above 500 HB fast structural applications restricted dual hard's use in the area of high tonnage combat vehicle requirements. Consequently, intensive studies were

initiated by AMMRC/MTL when the economic/cost limitations of Dual Hardness Steel became apparent. The studies and programs, some of which continue to this day, have focused on developing steel armor with Dual Hardness Steel ballistic properties, with significantly reduced cost and fabrication problems and improved structural integrity. One important result of the studies was the demonstration and verification that steels of higher quality (fine microstructure, fewer inclusions, and low sulfur and phosphorus) exhibit improved ballistic properties when compared to steels of lesser quality. This observation was demonstrated with steels of various as well as identical composition. Unfortunately, most of the steels were still too expensive to be considered armor candidates. With cost as a driver, AMMRC launched a full scale R&D program in the early 1970s which focused on the electroslog remelting process (ESR) process. The AMMRC effort also funded industry and university participation to exploit the process.

The ESR process was characterized by simple equipment, ease of operation and good metallurgical results. ESR ingot making capability had increased dramatically in that time frame; thus it emerged as the logical candidate to produce high quality, low cost steel.

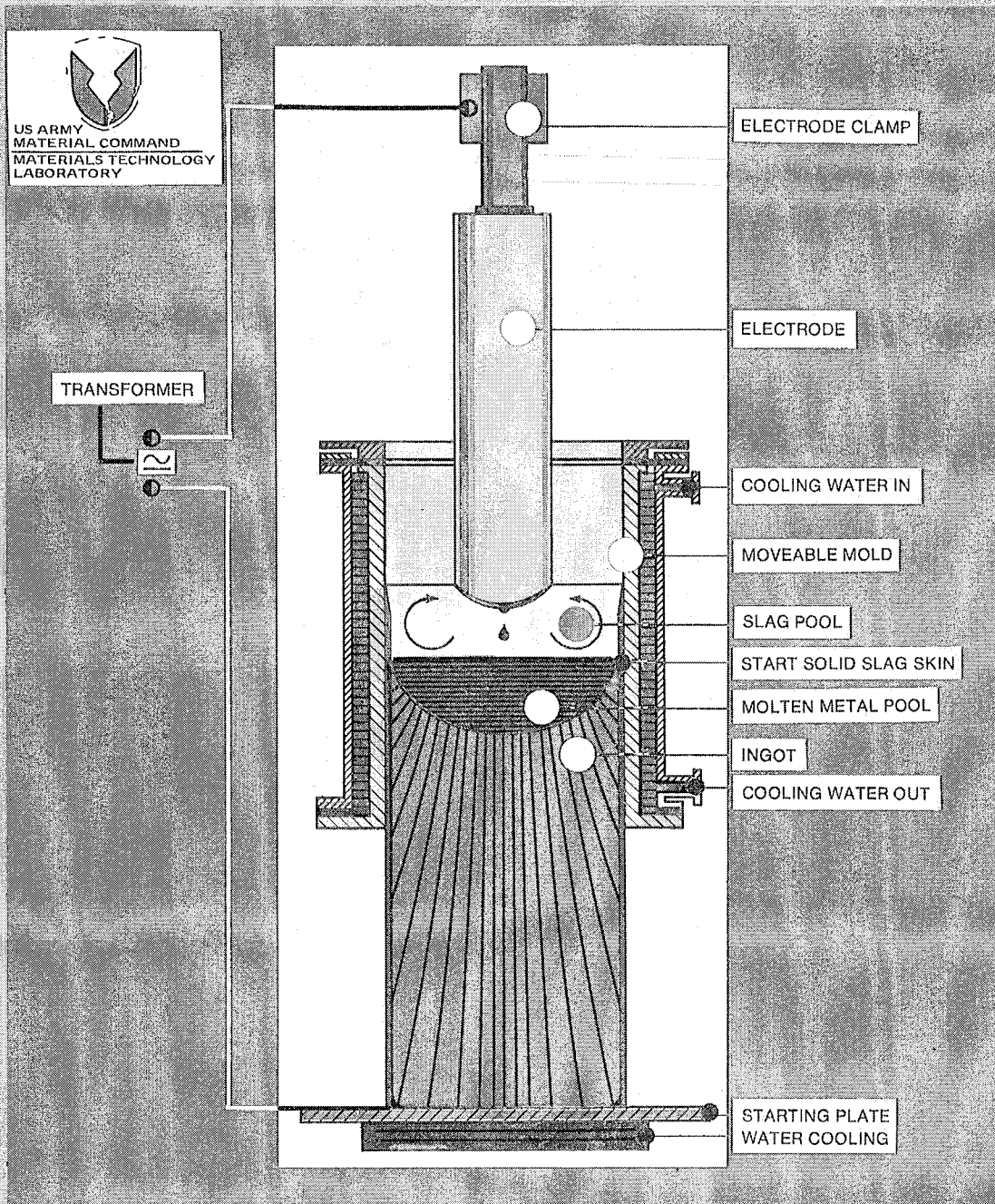
Electroslog remelting is a secondary remelting process in which an electrode is submerged in a molten slag bath and melted by passage of an electrical current. Droplets melt off the tip of the electrode, fall through the slag and collect in a pool on a water cooled base plate at the bottom of the slag bath. The slag is designed to remove sulfur from the steel.

AMMRC demonstrated dramatic improvements when conventional electric furnace (EF) 4340 steel was electroslog remelted. The improvement was characterized by greatly reduced sulfur and oxygen contents, resulting in reductions in nonmetallic inclusions. Subsequent characterization of the ESR and EF 4340 heat treated to the same hardness level of 53 HRC showed a four-fold increase in reduction of area (RA) for the ESR steel. A high RA is a measure of the steel's ductility and is generally necessary for good toughness.

It was concluded, therefore, that high strength ESR steels were major candidates for improved armor steels which could approach Dual Hardness Steel Armor ballistically and at a significantly reduced cost. The ESR process was thoroughly explored, and several alloys were characterized mechanically, metallurgically and ballistically. The AMMRC research and development resulted in the application of ESR steel/armor to two major U.S. Army aircraft: the Apache and Blackhawk helicopters.

Applications of ESR Steel

The manufacturer of the Apache (Hughes/McDonnell) had planned to use VAR 4340 steel in critical applications for



SCHEMATIC DIAGRAM OF ELECTROSLAG REMELTING UNIT

ballistic protection. When the manufacturer learned of AMMRC's research on ESR processing, the decision was made to substitute ESR 4340 steel heat treated to 53-55 HRC on over 100 critical components. These included projectile deflectors to protect the drive shaft and hydraulic heat exchangers. These were add-on armors. In addition, in a novel approach, Hughes/McDonnell made extensive use of the ESR 4340 for integral armor by designing components such as hydraulic actuators, rotor pitch links, bearing sleeves, crank assemblies and scissor links to be ballistically tolerant. By making these components from the high-hardness, high strength, tough ESR 4340 steel the components could sustain a hit and still continue to function.

In the Blackhawk helicopter ESR 4350 steel was used together with Kevlar in an aircrew seat. Reducing the cost and weight penalties associated with the application of aircraft armor has long been a standing goal of the armor materials community. With membership on the JTCG/AS Technology Research and Development Subgroup Armor Committee, AMMRC Metals and Ceramics Laboratory team members were certain that a cost effective, ballistically resistant crashworthy aircrew seat could be developed for a relatively small investment. A composite armor system consisting of 4350 ESR steel hardened to 50 HRC backed with Kevlar 29 was developed into a bucket seat configuration for combat helicopters. The 4350 ESR steel is required to achieve enhanced hardness levels, and the Kevlar provides an effective backup component to limit plate deformation and to capture projectile/armor fragments. Small arms/light machine gun threats, specifically 7.62mm AP and 12.7mm AP, are defeated at muzzle velocity and at range respectively.

During development, the optimization procedure and final ballistic testing represented a myriad of critical variables, such as alloy composition, heat treatment, areal density, projectile size and composite build up. Additionally, specific problems with seat welding needed to be resolved. The technical surmounting of problems enabled the production of a replacement crew seat for the Army Blackhawk helicopter, beginning in FY82. A cost reduction per aircraft of \$19,200 was achieved, and the savings over the remaining initial Blackhawk acquisition were in excess of \$15 million. The technology resulting from this effort was also integrated into Navy aircraft for additional savings. Cost savings realized through AMMRC's joint efforts effectively recovered one half of all costs for eleven years of JTCG/AS operations. The outstanding technical achievement in support of joint Service efforts was recognized by the awarding of the Joint DARCOM/NMC/AFLC/AFSC* Commanders' Certificate of Merit to four Watertown investigators.

In other developments, ESR 4353 and ESR 300M were both considered as candidate materials in the suspension systems of

* Army Development and Readiness Command/Navy Materiel Command/Air Force Logistics Command/Air Force Systems Command.

the Army's M113A1 and Bradley tracked vehicles.

During the 1980s AMMRC, and later MTL, conducted a number of studies on high strength ESR processed steels, with prime emphasis on ESR 4340. In 1985 a split heat study of vacuum arc remelted 4340 steel and ESR 4340 steel was undertaken to compare the hydrogen embrittlement (HE) susceptibility, mechanical properties and ballistic performance of steel produced by the two processes. The HE susceptibility comparison was subcontracted to Parker Hannifin Corp. The other two comparisons were performed by AMMRC. Investigations found that ESR 4340 steel was equal to or superior to VAR 4340 steel from strength, toughness and ballistic standpoints. That study may be the only controlled comparison study of the two processes done anywhere.

Although ESR processed material is as good as any type of processed steel being produced in the United States today it is still not widely used. Monetary considerations involved in conversion of production processes, the question of how much superior ESR steel is to steel produced by other new methods, e.g., ladle treatment, and exploratory research looking at other processes have all had an effect on the number of ESR applications within the military. Essentially, ESR was a superior technology for a window in time. During that time Watertown applied that technology to benefit Army systems.

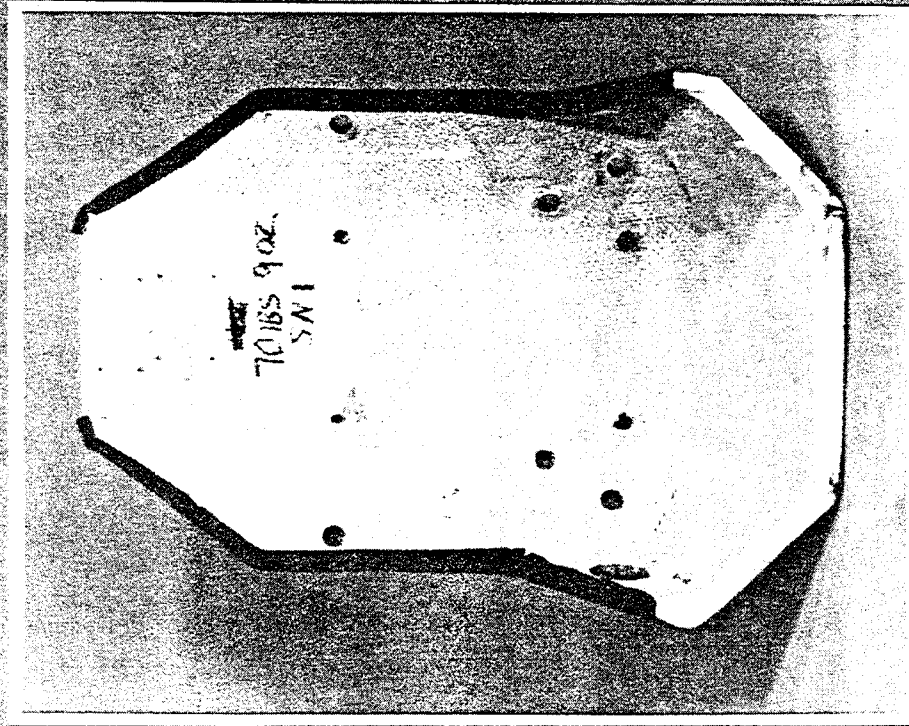
Gradient Hardened Steel Armor

Another study initiated by AMMRC/MTL to develop less expensive alternatives to Dual Hardness Steel Armor was the investigation of gradient hardened steels. Many innovative heat treating processes were performed on monolithic steels of various alloys. The objective was to produce a hard front surface for ballistic properties and a gradual reduction of hardness from the front to rear of the plate. The idea was that the cracks initiating at the front upon ballistic impact and propagating to the rear would be arrested prior to reaching the rear surface, thus avoiding catastrophic plate failure. In theory, the concept seemed feasible. In practice, however, most tests resulted in through thickness crack propagation and ultimate plate failure after one or more ballistic impacts. Extensive tests and observations at AMMRC led to the realization that the hardness gradients given to the steels were too gradual. It was suspected that a hardness gradient which more closely resembled that of roll-bonded dual hardness steel would be required. That is, hardness in the area of 60 HRC for approximately 50% of the plate thickness and 50 HRC for the remaining cross section. The technical objective thus focused on achieving a sharp drop from 60 HRC to 50 HRC over a short distance of armor plate mid-thickness.

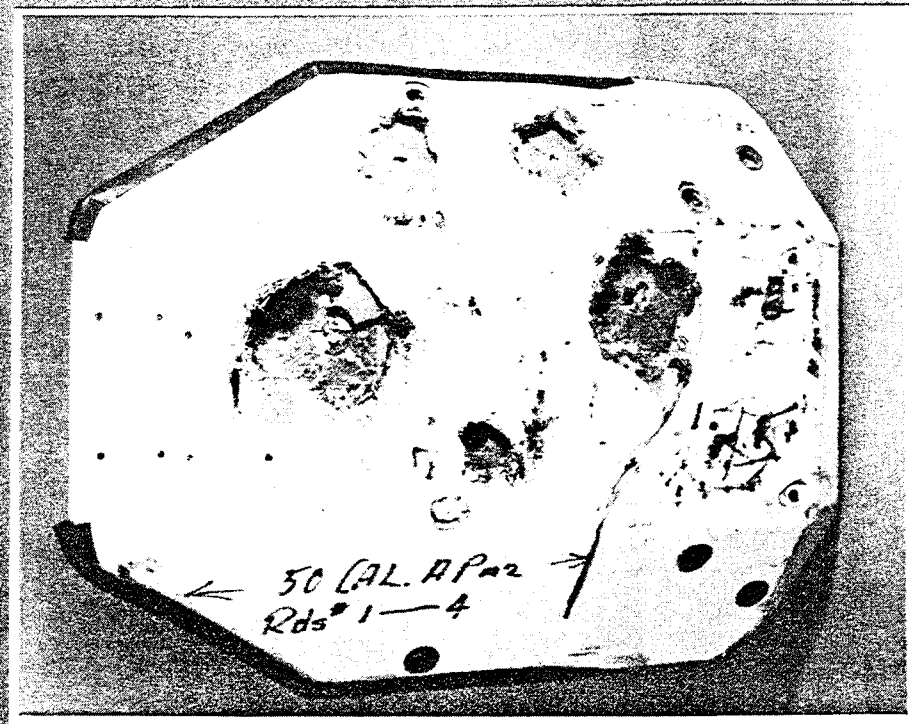
In the mid 1980s, AMMRC/MTL obtained state-of-the-art induction hardening/tempering equipment. In a cooperative effort

BALLISTIC-CRASHWORTHY AIRCREW SEAT

ESR STEEL/KEVLAR COMPOSITE ARMOR



FRONT VIEW



REAR VIEW

PASSED BALLISTIC REQUIREMENTS FOR .30 AP M2 AND 12.7 MM AP THREATS

with TOCCO Inc., the manufacturer of the equipment, Watertown developed the processing techniques to produce such skipped gradients. The results to date have been very promising. Ballistic equivalence and in some cases ballistic superiority to roll-bonded dual hardness steel armor has been demonstrated in steels with stepped hardness gradients. This development is continuing.

Light Metallic Armor Materials

Alloys of aluminum and titanium have been of interest for armor applications because of their low density and their ability to be processed to high strength levels. Magnesium alloys, although they have a lower density than aluminum and titanium alloys, have not been of interest for armor due to their pyrophoricity, relative low strength, and susceptibility to corrosion. Watertown has made very substantial contributions to the development of both aluminum and titanium armor alloys.

Aluminum Armor

The initial work on aluminum armor was begun in the early 1940s by Frankford Arsenal, Aberdeen Proving Ground and the Tank Automotive Command (TACOM) working in coordination with the aluminum industry.* The goal was a more weight efficient fragment armor. By the mid 1950s, this effort resulted in two medium strength aluminum alloys, 5083 and 5456, which are strengthened by strain hardening. These alloys have good weldability and corrosion resistance, and 5083 was used in the M113 Armored Personnel Carrier which went into production in 1960. This was followed by the development in the 1960s of a high strength, heat-treatable alloy 7039 which provided improved protection against armor piercing (AP) ammunition. The higher AP protection, however, was accompanied by a loss of resistance to fragment penetration and an increased tendency to back spall. In addition, the high strength 7000 series aluminum alloys are more susceptible to stress corrosion cracking (SCC). Nevertheless, 7039 was used in the M551 Sheridan Light Tank and in critical areas of the M-2 Bradley Fighting Vehicle.

In the 1970s and early 1980s, Watertown participated in efforts* to increase the strength of the strain hardening 5000 series alloy by increasing the magnesium content, and also to increase the SCC resistance of the 7000 series alloys. Watertown

* Until its closure in the mid 1970s, Frankford Arsenal was responsible for aluminum, magnesium and copper research and development.

received funding as part of this effort from the Marine Corps through the Program Manager for the Mobile Protected Gun System (PM-MPGS) at TACOM to conduct comparative tests on developmental alloys. The aluminum industry was invited to submit their most advanced aluminum armor alloys for tests of mechanical properties, SCC susceptibility and ballistic response. This study identified a new alloy, 2519, developed by ALCOA, as a promising candidate to replace 7039. It had superior ballistics and was SCC resistant.

In the early part of 1984, Watertown formulated a program at the request of PM-MPGS to extend this study to establish an engineering data base for application of lightweight laminate armor in design and fabrication of hulls and turrets for prototypes of a Mobile Protected gun (see Laminated Metal-Composite Armors). An extensive study of the mechanical properties including fatigue (for the first time), corrosion and stress corrosion resistance, welding, and ballistics were carried out. One important innovation in this work was a series of tests to determine the effect on the SCC resistance of aluminum alloys of long-time exposures at low temperatures (100°F to 212°F). This was done to simulate the expected changes in microstructure which would occur over the expected operational life of a combat vehicle.

A significant result was that aging did not sensitize 2519 to stress corrosion. However, 5083, which had been thought to be immune to SCC, was found to be highly susceptible to SCC after exposures of 10 days at 150°F and only 1 day at 212°F. This suggested that vehicles constructed of 5083 could be susceptible to SCC after service at high temperatures such as those found in desert environments. In fact, shortly after this study was completed, evidence of SCC was discovered in an M113 being overhauled at Red River Army Depot. Watertown was able to tell Red River what the probable cause was.

Overall 2519 appeared to be an excellent high strength armor alloy. A military specification was developed so the alloy is available for use in DoD applications. Its one point of weakness has been weld performance in a ballistic shock test. One type of weld (butt weld) withstood the same level of shock as 5083, but not the higher level called for with 2519 in view of its higher ballistic resistance. Watertown is currently examining approaches to developing higher strength welds via new welding wire filler alloy. So this last part of the story is still incomplete.

Titanium Armor

* Watertown linked with the metallurgists who moved from Frankford Arsenal to Picatinny Arsenal after Frankford closed.

Titanium armor development began in the late 1940s as part of the Watertown titanium development program (see The Early Years). The Ti-6Al-4V alloy developed by Watertown and which found widespread use as a structural alloy was also found to be the best armor alloy. It suffered, however, from a tendency to back spall. In 1963 it was shown that this problem could be alleviated by specifying an extra low interstitial (ELI) grade which increased ductility. A military specification MIL-A-46077 was developed to incorporate this finding. Material produced under this specification was ballistically superior to the steel and aluminum armor alloys existing at the time but was more costly.

Titanium made to this specification was briefly used as modular armor on trucks and riverine craft early in the Vietnam conflict. In 1964 Watertown briefed General Besson, the Commanding General of AMC, on titanium and its suitability for such applications. As a result of the briefing, Gen. Besson authorized non-competitive procurement of titanium for this use, and Watertown executed the procurement to supply titanium armor to Vietnam.

Within a year, however, Watertown discovered that steel armor hardened to 50 Rockwell C (high hardness steel armor now procured to MIL-A-46100) offered the same ballistic protection on an areal density basis, and it was much cheaper than titanium. Even though the early versions of high hard steel armor suffered from low temperature brittleness, the ambient temperature in Vietnam was above the ductile-brittle transition temperature, so Watertown recommended substituting the steel for titanium. This ended titanium's brief use as an armor for ground vehicles. The high cost of titanium continued to preclude it from serious consideration for armoring ground vehicles until the late 1980s and early 1990s.

There are several reasons for this renewed interest in titanium for ground vehicles. One is the challenge of avoiding growth in vehicle weight in the face of a continued increase in the severity of threats to the vehicles. The increased threat motivated the Program Manager for the Bradley Fighting Vehicle (PM-BFV) to consider and then use Ti-6-4 for the commander's hatch located on the top of the turret. The hatch had been made from 7039 aluminum in the first three versions of BFV's. In the late 1980s, requirements for increased protection would have required a large increase in thickness if 7039 were still to be used. Steel would be too heavy, and a composite hatch with ceramic and glass would be too complex and expensive. Therefore, FMC, the manufacturer of the BFV, recommended titanium. Working with the Wyman-Gordon Company, FMC developed a forged Ti-6-4 which met the requirements and which was fielded in 1993. Watertown contributed by recommending that the Ti-6-4 be used in the annealed condition to obtain the optimum microstructure.

Another reason is the potential for lower cost. Several factors have combined to produce a much more affordable "Low Cost" material. One factor is the availability of a very low

cost sponge (below U.S. producer prices) from the Former Soviet Union which had built up extensive titanium capacity, enabling it to undercut the prices of other nations. Secondly, new melting methods (hearth melting) are being employed. A third factor in titanium's new affordability is reduced specification requirements, especially regarding oxygen which allows the use of more revert and scrap. It is no longer necessary to specify an extra low interstitial content as in MIL-A-46077. The expectation is, that due to the titanium industry having improved cleanliness overall, back spall should not be a problem in using titanium as an applique or component in a more complex armor system. Significantly, in the BFV commander's hatch program, it was found that it was unnecessary to specify material to the cleanliness level called out in MIL-A-46077.

A third motivation is the Army need for lighter, more easily transportable vehicles and weapons systems. The emphasis on titanium as the material of choice results from titanium's unique combination of properties, including high strength-to-weight ratio (compared to steel) with good ductility; and secondly, high mass efficiency (E_m) of about 1.5 compared with RHA steel for all ballistic threats. Another advantage to titanium is its excellent corrosion resistance. Finally, titanium is both weldable and machinable. (Historically, personnel at Watertown were the first to develop techniques to machine titanium.)

As a result, Watertown, BRL (now the Weapons Technology Directorate of ARL), and TARDEC have been working closely with the Titanium Development Association (TDA), the Bureau of Mines (still involved in titanium metallurgy), and the titanium manufacturers on application of titanium to other Army systems. Both ARL-MD and WTD have been ballistically testing low cost titanium alloys produced by the three U.S. titanium companies. In addition, ARL-MD personnel played a major role in establishing a Military Applications Committee within TDA in 1991.

Currently, Watertown is working cooperatively with both ARDEC-PRWB (Productions Readiness Weapons Branch) and TARDEC on various aspects of the application/implementation of "low" cost titanium on vehicle/weapons systems.

The program with ARDEC-PRWB consists of an evaluation to determine the current and future statuses of titanium applications, fabrication and production requirements applicable to the AFAS/FARV systems. Utilizing system/vehicle information obtained in conjunction with TACOM, a titanium trade-off analysis will be conducted on the AFAS/FARV to determine specific material requirements. In addition, the identification of current titanium resources and companies will be made in order to assess the refining/processing methods utilized and the associated costs. Existing field welding processes and procedures will be identified and any deficiency will be addressed.

The proposed program with TARDEC consists of a proposal to design and test a Low Cost Titanium turret for the M1 Abrams main battle tank. The results of this cooperative titanium program

will provide a highly valuable database which can be independently applied to current and future vehicles and weapons systems, bringing titanium into the 21st century.

Transparent Armor

Single Crystal Sapphire (Al_2O_3) for Transparent Ceramic Armor

As noted in the earlier section on ceramic armor for aircraft/air crew protection, helicopters in Vietnam were vulnerable to small arms AP threats. The lightweight ceramic armors developed in the early 1960s by Watertown and the Army Aviation community provided protection to the crew and to critical components from most shot lines except those directed through the canopy toward the face. Polycarbonate and glass-polycarbonate laminates were efficient against ball projectiles and fragments, but not against AP. This required a transparent armor ceramic backed by polycarbonate.

The development of a transparent ceramic presented a challenge. The ceramic must be hard to be an effective armor. Transparency to visible light requires the ceramic to be a good insulator (wide band gap), to be of sufficient purity to avoid color centers, and to be free of defects which scatter light. The first two requirements eliminated virtually all of the armor ceramics except sapphire (aluminum oxide, Al_2O_3). The problem with Al_2O_3 is that it has a non-cubic crystal structure. In non-cubic crystals the index of refraction varies with crystal direction. As a result, light is refracted as it passes from one crystalline grain to another. Since most polycrystalline ceramics have grains on the order of a few micrometers in size, there would be thousands of refractions per centimeter as light passed through the ceramic. The multiple refraction destroys image coherence so polycrystalline sapphire would be translucent, not transparent, even if otherwise defect free. Therefore, to be transparent the Al_2O_3 must be in the form of a single crystal, or the Al_2O_3 must be alloyed to produce a cubic crystal structure. Watertown eventually developed transparent ceramics using both approaches. The development of a technique to produce a single crystal Al_2O_3 was achieved first and will be described here. The development of nitrogen-stabilized cubic Al_2O_3 , which was a serendipitous discovery, is described in the section on Electro-optical Materials.

Watertown pursued several approaches to producing Al_2O_3 single crystals both in-house and on contract. Attempts to produce transparent plates by the chemical vapor deposition process and to grow relatively large single crystals by the Verneuil technique were not promising. Watertown-sponsored work at Union Carbide Corporation for the development of manufacturing

processes by the Czochralski method did result in the production of single crystals with dimensions of 3 by 6 inches, suitable for a mosaic transparent armor window. Existing techniques, however, could not be scaled up for economical fabrication of large single crystals. A technique akin to directional solidification with more control was required to grow large, high quality single crystals in large quantities.

The Heat Exchanger Method: Watertown researchers conceived of a method whereby the heat could be removed from the crystal with a high temperature heat exchanger, eliminating the need for motion of the crystal, crucible or heat zone. In essence, this method involved directional solidification from the melt where the temperature gradient in the solid could be controlled by the heat exchanger, and the temperature gradient in the liquid could be controlled by the furnace temperature.

To accomplish this, Watertown personnel developed a helium gas-cooled heat exchanger to control heat extraction at high temperatures. Helium gas was chosen since it was inert and would prevent oxidation of refractory metals; helium also had a high specific heat and good thermal conductivity. The heat exchanger was installed in a well-insulated vacuum resistance furnace to provide essentially an isothermal heat zone. The temperature of the heat exchanger surface was controlled by the flow rate of the helium gas and through the heat exchanger. The process was initially known as the Heat Exchanger Method (HEM).

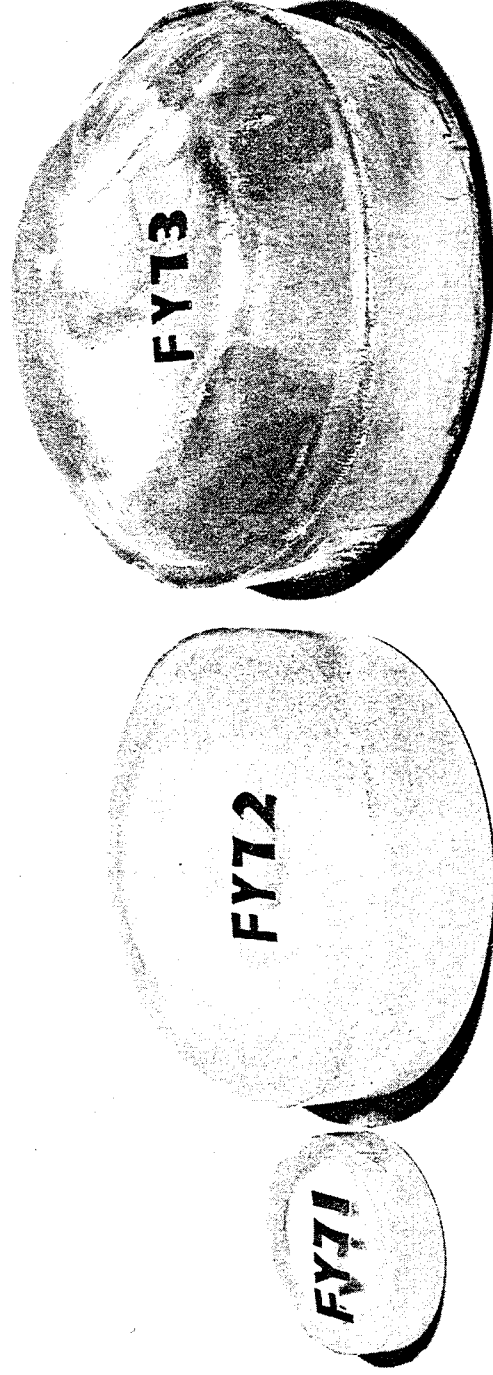
Initial attempts met with mixed results. Anisotropic thermal expansion due to the non-cubic crystal structure of Al_2O_3 , caused cracking at the grain boundaries of the very large grain multicrystalline alumina ingots that were produced. However, it appeared that heat flow could be controlled sufficiently to seed and grow from a single crystal sapphire seed in the bottom of the crucible. This was demonstrated in 1969; a U.S. patent was issued in 1969.

On the basis of this work it appeared that larger diameter crystals could be grown by using a much larger crucible. A molybdenum crucible loaded with Al_2O_3 chips was seated on the tungsten heat exchanger. The furnace was evacuated and heated above $2050^{\circ}C$, the melting point of Al_2O_3 , and then the temperature was stabilized. The heat exchanger temperature was increased by reducing the helium flow through it to allow the alumina to melt into the seed crystal and nucleate it. When the alumina had melted into the seed, the heat exchanger temperature and furnace temperature were adjusted to cause the crystal to grow from the seed across the entire bottom of the crucible. Temperature gradients in the solid and liquid were controlled by the heat exchanger and furnace temperature respectively. Constant growth rates were achieved by decreasing the liquid and increasing the solid gradients simultaneously.

Crystals grown by this technique at Watertown were three



A mosaic single crystal sapphire faced transparent armor, constructed of sapphire crystals grown at Watertown.



PROGRESS OF SAPPHIRE SINGLE CRYSTAL GROWTH

The early 1970s saw rapid progress in the growth of transparent sapphire single crystals at Watertown. The crystals grown in 1972/1973 were the largest diameter sapphires ever grown at that time.

inches in diameter, and one-half inch thick. Reproducibility was demonstrated by growing numerous crystals. On the basis of these results, it appeared that the process could be scaled-up to grow large diameter sapphire for transparent armor window applications. The furnace chamber was enlarged to accommodate a six-inch diameter crucible. The technique was unchanged except that the growth time was increased by about a factor of two.

The six inch diameter boules were cut into hexagonal blanks and polished to make one of the first large transparent armor windows that measured about 14 by 16 inches. The Watertown researchers received a Department of the Army Research and Development Achievement Team Award in 1971 for this work.

Technique Flexibility and Tech Transfer: HEM is the only crystal growth process where liquid and solid temperature gradients are controlled independently without moving the crucible, heat zone or crystal. The crystal is grown under a stabilizing temperature gradient to minimize convection of the melt. Heat extraction for growth is controlled by the heat exchanger while heat input is controlled by the furnace temperature, both of which are controlled throughout the cycle. Because there is independent control of the heat extraction and input in HEM, the crystal can be in situ annealed to reduce the solidification stress and defect density.

This technique is further distinguished from all earlier techniques in that the solid/liquid interface advanced three dimensionally. Radial temperature gradients are produced by the heat exchanger to form a hemispherical liquid/solid interface. As the solid temperature gradient is increased, the solid/liquid interfacial area grows larger at the same rate as the crystal enlarges. The expanding growth interface results in large effective growth rates even though the one dimensional growth rate remains constant.

The flexibility of the technique has been demonstrated by growing various materials, shapes, and even sapphire molybdenum composites. The unique features of HEM, combined with the ability to control cooling to room temperature, made it possible to grow the world's largest sapphire, 33cm in diameter and weighing over 50kg.

In 1971 one of the inventors left Watertown with AMMRC's encouragement to form a company Crystal Systems, Inc. to develop the technique for commercial application. This company has successfully employed the HEM for the production of sapphire and other single crystal materials. The combination of sapphire's desirable optical and mechanical properties, and its availability in large size, makes it the material of choice in a variety of modern "high tech" applications, such as environmental, space and military optical systems as well as high-power laser optics, high-pressure components and semiconductor substrates. Large, high-quality sapphire is now used for many commercial and military optical applications. Sapphire is a particularly

important IR window material in advanced high-speed missiles that require high IR transmission combined with high thermal-shock resistance in military applications.

HEM has significant potential for producing larger and higher quality crystals than are possible with any other technology. Process research and development by the private sector continues to develop the capabilities of HEM. What began at Watertown as research for a ballistic aircraft windshield has, through technology transfer, become the story of a growth industry.

Stretched Polypropylene Radar Transparent Armor Materials

Although the term "transparent armor" usually refers to transparency to visible light, Army applications also require transparency to other wavelengths of electromagnetic radiation. One such application is transparency to radar frequencies.

In 1974, the Army undertook development of the Firefinder radar system to track artillery shells back to the source location in order to silence the gun by counter-battery fire. Since this radar would be exposed to battlefield threats such as shell fragments, there was a requirement to armor the radar system.

Watertown was requested by Electronics Command (COM), Ft. Monmouth, to undertake development of a radar transparent armor material for radar antenna hardening. The program focused on utilizing high strength polypropylene film produced by stretching conventional polypropylene film to 12 times its original length, thereby creating a highly oriented molecular structure. Polypropylene was chosen because of its favorable dielectric properties relative to the radar frequencies of interest, and because multiple film layers could be laminated to finite thickness to form tuned wall panels (equivalent to $1/2$ wavelength). The ballistic performance of these laminated stretched film panels was nearly equivalent to Kevlar panels versus fragmentation threats. For 1" thick panels (weighing 5 lbs/ft²), consistent for a $1/2$ wavelength tuned wall thickness for the AN/TPQ-37 radar system, most of the fragments from conventional munitions at reasonable standoff would be defeated, thereby protecting the antenna.

Initially, Watertown worked with Phillips Petroleum at their Bartlettville, Oklahoma, research laboratory to develop stretched-oriented polypropylene for armor applications. Following a number of iterations, processing parameters (temperature, stretch ratio, etc.) were optimized to achieve the desired high tensile strength film, which in concert with polypropylene's low density ($P=0.95$), produced a high efficiency fragmentation armor (designated XP). The technology was extended to produce rigid armor panels through an extensive in-house R&D

program to determine the lamination parameters and to establish production methodology. It was determined at Watertown that pressures in excess of 1,000 psi and temperatures within the 345-350°F range were required to achieve the required laminated panels. The high pressures are required to maintain the XP's film orientation and strength during the lamination process. The XP layers are laminated to one another through temperature and pressure with no additional bonding material (i.e., resin), thereby maintaining the desirable dielectric properties. Through contractual efforts at Swedlow, Inc. (Garden Grove, CA) and Youngblood Laminates (Millbury, MA) production size high quality panels measuring 36"x24"x1" thick were fabricated and subsequently electronically tested at ECOM and the Electronic Space Systems Corporation (Concord, MA) for radome applications. The "Electrical Design Analysis" for XP Panel radome applications revealed that negligible transmission losses occur (<1dB for frequency bands ranging from 1.5 to 22 GHz), with acceptable boresight errors (<1mrad). These values confirmed the "Proof of Principle" that the XP materials could be used for ballistic resistant radomes.

A problem arose, however, when ECOM chose a phased-array radar to maximize tracking speed. In phased array radar the antenna is not physically moved to steer the beam; but rather the antenna remains stationary and the beam is steered electronically. This provides very rapid tracking, but it meant that the beam was at normal incidence to the film only when the beam was looking straight ahead. When projected off normal incidence, the beam traversed an increasing thickness of the armor as the obliquity increased. Thus, the beam and the reflected image become distorted. Today with the increasing sophistication of computer chips this could be corrected for in real time. In 1980, it was not feasible. Therefore, the stretched polypropylene film was not used, and the system was armored with thin Kevlar panels, placed in front and behind the emitter/receiver. Nevertheless, the approach of stretching a polymer to orient the molecules to increase the strength of the material was established, and used later by Allied Signal to produce their Spectra high-strength polyethylene fiber for personnel armor (see Personnel Armor for Ground Troops).

Armor Design Handbooks

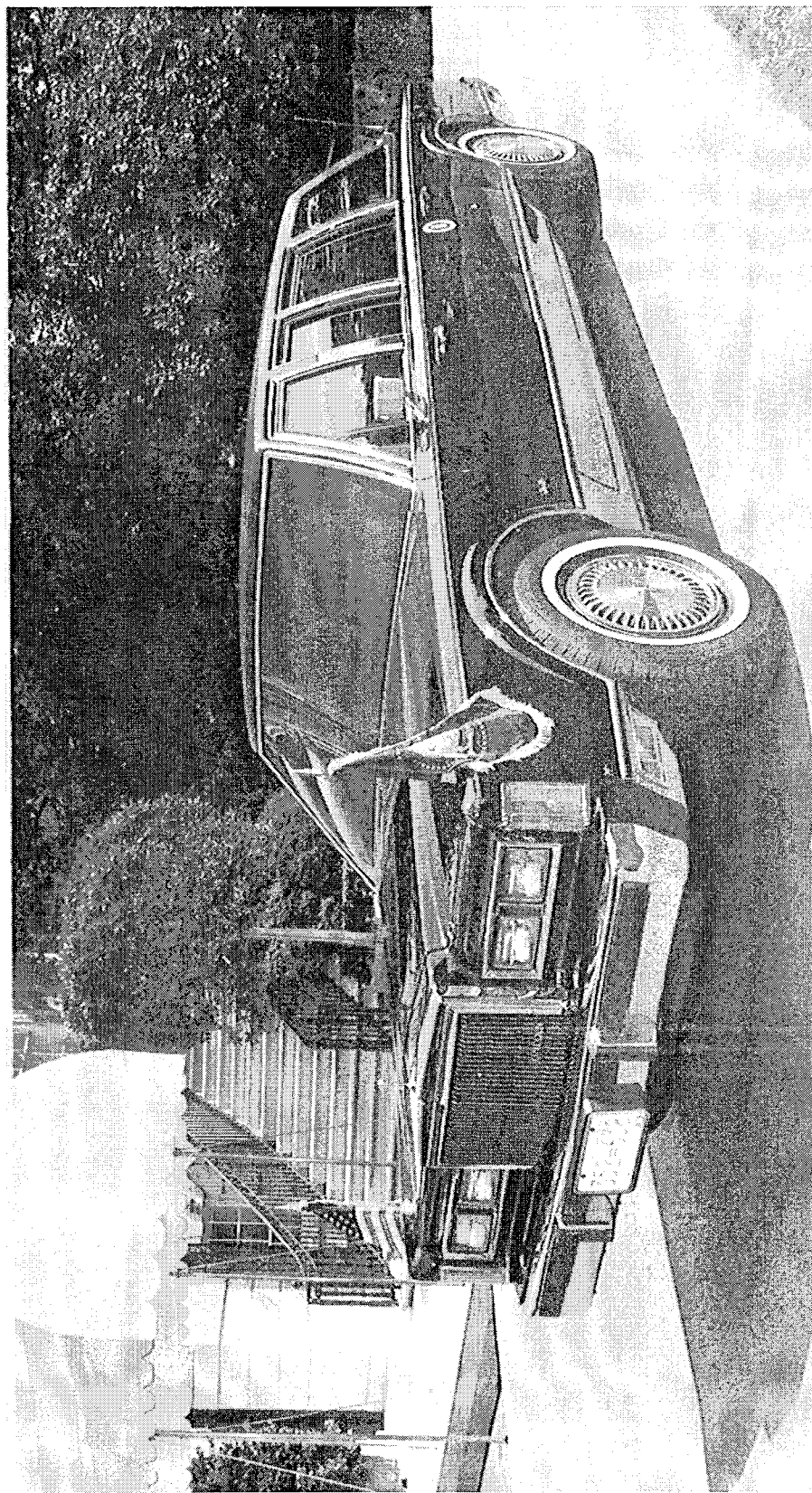
At the outset of World War II, steels were virtually the only materials used as armor, with various thicknesses providing different levels of protection. As aluminum began to be more widely used for military applications, however, its potential as an armor material also needed to be considered. This immediately exposed the need for a quantitative method to compare the relative ballistic efficiencies of materials with different mass densities. Since weight was the dominant concern in armor

design, it became customary to express the thickness of an armor in terms of its weight per unit area (e.g., lbs./sq.ft.) or its areal density. Levels of protection also began to be expressed in terms of a "protection ballistic limit" (V_{50}), defined as that velocity of a given threat projectile which has a 50% probability of penetrating the target armor. For a given armor material having the same set of physical and mechanical properties, a unique relationship was found to exist between the protection ballistic limit provided against a given threat and its areal density. The relative ballistic efficiencies of different materials thus could be compared by determining which provided a given V_{50} at the lower areal density or which material at a given areal density provided the higher V_{50} . On this basis it was shown that aluminum armor could be superior or equal to steel armor against many battlefield threats.

This discovery stimulated a comprehensive investigation by Watertown and other government and industrial laboratories in which the ballistic capabilities of a range of candidate armors and composite armor systems were evaluated. The more promising of these were evaluated over a range of areal densities and threat levels representing probable battlefield conditions, establishing a series of design curves of V_{50} versus areal density. These curves were developed, collected, and in 1981 published as AMMRC TR81-20 entitled "Ballistic Technology of Light-Weight Armor." This armor design handbook became the key reference for all designers of lightweight armor systems since it provides the basis for the comparative ballistic performance of many different candidate armor materials versus a variety of conventional ballistic threats. It is widely used to this day.

In recent years with the proliferation of weaponry from various sources, the number of design curves required to define all possible threats has become enormous. It therefore became desirable to reduce this number by developing a design system based on generalized battlefield threats. The concept of a series of generic threat projectiles, each of the same basic design (AP, ball, FSP), was developed at Watertown, enabling the definition of a single design curve for all size projectiles of that generic type. These design curves are a plot of protection ballistic limit versus a new parameter called "Armor Demand," which is areal density expressed as a function of projectile diameter. This Armor Demand design system enables the determination of the weight of an optimum armor system required to defeat any small arms projectile of that type as well as all shell fragments within the range 1.35-830 grains in weight. These Armor Demand design curves are published in MTL Report TR90-40 entitled "Lightweight Armor Design Handbook--Monolithic Armor."

Executive Protection



Recognized worldwide as innovators in ballistic protection, the U.S. Army advises the secret service regarding protection for the president of the United States.

Army Research, Development and Acquisition Bulletin, July-August 1981.

Following the assassination of President Kennedy in 1963, AMMRC engineers conducted a threat analysis to define the most likely methods which might be used to kill an executive. Based on this analysis, they made specific recommendations to the Secret Service and the Department of Defense for armoring the President's limousine for protection against these threats. AMMRC provided consultation to the Secret Service and a contractor while the limousine was being armored. It was finished and delivered to President Johnson in the short time of 13 weeks. This limousine provided protection from small arms ammunition, blasts from dynamite, and poison gas, among other threats.

Since that time, AMMRC engineers and their organizational successors have been consulted regarding several other limousines which have been armored for the President's use. Each has provided more protection than its predecessor as new technology has been incorporated into each emerging design. Reinforced by public law 94-524, this relationship between Watertown and the Secret Service has been an important part of the total armor program of the Secret Service. The then current Director of the Secret Service asserted in 1983 that "the significance of the efforts of AMMRC in this area in assisting the Service in the protection of the President cannot be overstated." For example, AMMRC personnel played a key role in ensuring that the parade limousine delivered in 1984 was the strongest armored passenger vehicle in the world. In the mid 1980s the Secret Service requested additional direct participation from MTL in the program in the form of actually assembling the new composite armor panels prior to contractor installation. In commenting upon this request, the Secret Service Director stated that "This arrangement guaranteed us not only the best national expertise and skills, but also a degree of security and flexibility not possible in the private sector."

During these years of cooperative effort, the President's helicopter was also provided with Watertown-developed armor to protect critical components of the aircraft.

In another utilization of Watertown expertise, the State Department asked AMMRC engineers to design armor kits which could be applied to commercial limousines used by ambassadors and other diplomats and personnel living abroad. These kits were applied to existing limousines by the General Services Administration and are still being used by the State Department.

The importance of the collaborative relationship between the Army Laboratories at Watertown and the Secret Service and between Watertown and the State Department has been underscored by the world-wide increase in terrorism and violence. For more than twenty years members of the Composites, Reproducibility and Mechanics staff at Watertown have provided an interdisciplinary and interdivisional response to meet the needs of the government's protective mission. A testimonial delivered by the Secret Service stands as a fitting tribute to the entire armor program at Watertown: "We sincerely believe that MTL has

developed a base of both engineering and technical staff which is unsurpassed in the field of armor materials and technology."

Armor Conclusion

One point to be kept in mind in reviewing the history of Watertown's armor research is that the particular application and need affected the choice of armor material. According to its specific application, armor requirements were defined in terms of protection requirements, usually established by casualty analyses, along with other requirements, including: configuration, availability, fabricability, cost-effectiveness and physiological effects, including weight limitations.

These requirements were defined by the Army's user/development community. This community was made up of the Forces Command, i.e., the troops in the field; the Training and Doctrine Command, which develops the concepts of how the Army will fight; and the Commodity Commands, who have the responsibility to develop systems to implement those concepts. Watertown's unique capability has always been its understanding at the "cutting edge" level of the various types of materials, how these materials are, or might be, modified and produced, and the properties which could be expected. By working as a team with the user/development community to mutually understand the demands put on the material by the application, Watertown was able to recommend, modify, or develop the right material for the application.

The preceding pages on armor have focused on Watertown's applying its expertise to defensive protection measures. The next section, Armaments, highlights Watertown contributions in the development of Army weapons systems.

ARMAMENTS

High Density Materials for Armor-Piercing Projectiles

During the 1930s the first experimental testing of tungsten carbide (WC) as an armor-piercing (AP) projectile was conducted at Watertown. Because WC has a much higher hardness and greater mass density than steel, WC proved to be a more effective penetrator against steel armors. Scaling the results up to 76mm and 90mm sizes utilized sub-caliber penetrators for the first time, i.e., the diameter of the penetrator was less than the bore diameter of the gun. WC penetrators 1.5" in diameter and 2" in diameter were held within an aluminum carrier which fit the 76mm and 90mm guns respectively. Because each of these projectiles was lighter in weight than the standard steel AP projectiles, they had higher muzzle velocities. These high velocity armor-piercing projectiles (HVAP) were used by the Allied Forces during World War II where they were capable of perforating the frontal armor of German tanks.

Following World War II, WAL developed improved compositions of WC and also developed plastic discarding carriers for launching the WC penetrators. The sub-caliber WC penetrator with a thin aluminum windshield was encased in a plastic carrier which was discarded from the projectile after launch, greatly reducing the aerodynamic drag on the penetrator as it flew to the target. An experimental 76mm AP round based on this concept, the T89E3, was developed which could be fired at much higher velocities than the 76mm HVAP round (5000 fps vs. 3200 fps). However, the T89 was never adopted because the plastic carrier would melt if it remained in the chamber of a hot gun for a few minutes, adversely affecting the flight stability and accuracy of the projectile. Nevertheless, the concept of a discardable carrier in which to hold the sub-caliber penetrator during launch became the basis for the development of all subsequent AP tank rounds from the 1950s through today, all of which use discarding sabots to achieve high velocities.

After World War II continuing experiments with new projectile designs had shown that long slender rods of high density materials would penetrate armor better than conventional AP ammunitions. Hence there began a series of developmental long rod penetrator munitions in which the ratio of length to diameter of the penetrator was 10 or greater, as compared with about three for the conventional design. This geometry placed much more stringent requirements on the penetrator material in order to ensure adequate launch integrity. WC was unable to meet these requirements and so the search for better materials was on. Watertown was at the center of that search and followed two separate approaches: tungsten alloy research and depleted uranium (DU) alloy development.

Watertown had been conducting research on uranium alloys

since the late 1950s. The goal of this research was to develop easily processable high strength, high hardness alloys which would show good ballistic performance, but which retained adequate ductility and toughness to enable them to be gun-launched without failure. Several alloys were developed at Watertown which contained various combinations of Nb, Zr, Mo and Ti up to a total alloy content of three to four %. While some of these so called Quad and Quint alloys showed good promise, the relatively high alloy content reduced the available alloy density below desired levels. Therefore the Army chose to adopt the alloy DU-3/4% titanium for its first DU penetrator round, the M774, in the late 1970s. All research on DU focused on this alloy from that point on.

In 1977 Watertown became involved in the investigation of a low temperature firing failure of a M774 projectile. Working closely with the staff at Picatinny Arsenal, Watertown was able to demonstrate that directionally quenching the DU penetrators during heat treatment produced higher fracture toughness properties than the conventional quenching method. In so doing Watertown was able to establish a minimum fracture toughness requirement which was incorporated for the first time in DU penetrator specifications.

During this period and beyond, Watertown investigated extensively the corrosion characteristics of DU. Concern for potential corrosion and stress corrosion of DU alloys proved to be justified when inspection of penetrators in long-term storage disclosed significant corrosion damage. To provide corrosion protection of future DU penetrators Watertown engaged in research on various sacrificial and barrier coatings which culminated in the development of an aluminum-zinc coating deposited by a cathodic arc plasma PVD process. This coating was selected for protection of the 25mm long rod penetrator system, M919APFSDS-T, and earned for the Watertown technical staff a 1992 R&D Achievement Award nomination.

Meanwhile research at Watertown to improve the mechanical strength and toughness of DU-3/4 Ti was investigating thermomechanical processing methods. A process was developed which applied a combination of warm and cold deformation treatments to solution treated and aged DU-3/4 Ti. The results were increases in yield strength of up to 150% that of the conventionally processed alloy without any reduction in fracture toughness. Ballistics tests showed a corresponding improvement in armor penetration performance. This kind of thermomechanical processing has not yet been applied to any fielded penetrator round, but it has been used in other applications requiring ultra-high strength uranium alloys.

The possible application of tungsten heavy alloys (WHA) to kinetic energy penetrators was first explored at Watertown in the early 1970s. The initial application was to be the M735 projectile. This alloy had a composition of 97% tungsten with the balance being nickel, iron, cobalt and copper. It was chosen for its density which matches that of the uranium-3/4% titanium

alloy, the alloy of choice. It has been long recognized that uranium alloys used for kinetic energy penetrators outperform those made from tungsten based alloys. In the 1970s and most of the 80s the primary focus for closing this gap was to improve the mechanical properties of the tungsten alloys, particularly the tensile strength and various measures of toughness or ductility. This led to development of tungsten heavy alloys that sacrificed density for improvements in these properties. The alloys which were developed had tungsten contents that ranged from 90 to 95 weight % and matrices containing varying amounts of nickel and iron. Property improvements were observed, but ballistic performance still remained inferior to DU alloys. The microstructure of a tungsten heavy alloy consists of tungsten grains bonded together by a matrix alloy. When the tungsten contents are high, as in these alloys, there is insufficient matrix to isolate the tungsten grains. The contact between tungsten grains is called contiguity and can be as high as 40% in 95% tungsten alloys. About this time, research reported in the literature indicated that contiguity of the tungsten grains in the heavy alloys was a significant factor limiting the ductility of these materials. The tungsten grain contacts are the weak link, and Watertown personnel determined that eliminating these contacts would improve the ductility of heavy alloys. Based on this hypothesis a Small Business Innovative Research (SBIR) contract was awarded to Ultramet, Inc., Pacoima, CA to develop the techniques for coating tungsten powders with the matrix alloying elements. Coated tungsten powder combined with solid state consolidation would potentially eliminate contiguity. This effort was very successful; chemical vapor deposition (CVD) was used to coat tungsten powder particles with nickel and iron, singly and as an alloy. Consolidated by solid state techniques, the Ceracon process, this powder made a very tough, high strength alloy. Ductility improvements approached 100% while strength improved by 50%. Ballistic testing of this material showed no improvement in performance. The coating techniques developed for these alloys are now being used to fabricate cemented tungsten carbide for cutting tools. The toughness improvements will greatly benefit these materials.

Even though incremental improvements in tungsten properties had been obtained, the Army made the decision to utilize depleted uranium in its penetrator rounds based upon the superior ballistic performance of DU. The ensuing environmental and geopolitical concerns over the hazards of DU, however, caused a resurgence of interest in tungsten.

In the mid-1980s a DARPA funded, Watertown managed, contract with GTE Sylvania, Towanda, PA examined the effect of processing, alloy content and thermomechanical treatments on the ballistic performance characteristics of kinetic energy penetrators. Despite significant improvements in the mechanical properties no effect was observed in the terminal ballistic capability. At approximately the termination of this contract, a breakthrough in the understanding of the ballistic penetration process by

personnel at the Ballistic Research Laboratory (BRL) (now ARL-WTD) led to a new approach in developing tungsten penetrator alloys.

The breakthrough involved a description of the failure mechanisms active at the nose of a kinetic energy penetrator as it burrows through an armor. It was found that two mechanisms govern the behavior of the WHA and DU penetrator alloys. The DU alloys were found to be superior due to their ability to self-sharpen during penetration while the WHAs form mushroom noses that consume the kinetic energy. The self-sharpening behavior is a result of a phenomenon known as adiabatic shear, a deformation mode that results in intense plasticity in a very narrow band (see this topic under Basic Research). This action results in shear of any mushroom petals before a head can be formed. Adiabatic shear did not occur easily in the tungsten heavy alloys investigated up until that time. These observations had the consequence of changing the direction of tungsten alloy research.

As of about 1990 the tungsten alloy work at Watertown was focused on developing tungsten alloys or composites that would behave like DU alloys in terminal ballistic applications. It was also at this time that Watertown entered into a memorandum of understanding with ARL-WTD, Aberdeen and ARDEC, Picatinny Arsenal to cooperatively develop tungsten based materials that would be ballistically equivalent to DU alloys. Two paths were followed. The first, called flow softening, sought to develop adiabatic shear-like failure mechanisms in tungsten materials. This method necessitated finding alloying elements to replace the traditional nickel-iron matrix. The search compared the properties of DU alloys (known to be susceptible to adiabatic shear) to other alloys believed to be compatible with tungsten. Also included were materials known to develop adiabatic shear when used as armor materials. Examples are high strength armor steels and titanium armor alloys. Many other materials were considered; these included brass alloys, hafnium, nickel-manganese alloys, intermetallic compounds and zirconium. As of this writing the most successful of these are the composites based on tungsten-hafnium.

The second path, referred to as flow anisotropy, examined several means to develop selected failure paths as a means of preventing the mushroom head. The first of these was the fabrication of laminated tungsten composites. These layered, one-dimensional, composites alternated tungsten heavy alloy layers with those of copper or nickel braze alloy. Ballistic testing of these materials led to incremental improvements in performance and highlighted scale factors in the laminations. Follow-up work in this area, at this writing, is intended to pursue two-dimensional composites of tungsten and materials shown to adiabatically shear. Two-dimensional composite configurations to be looked at are jelly roll and tree ring-like laminates. A second flow anisotropy approach is the use of tungsten single crystals with the [100] orientation on the long axis. The benefit of this approach was demonstrated by ballistic tests at

BRL. The cost and availability of tungsten single crystals was prohibitive until Materials Directorate personnel identified sources of tungsten crystals in the former Soviet Union (FSU), specifically Russia and Ukraine. These crystals are of sizes sufficient to fabricate full scale penetrators and are potentially cost effective. Characterization of these crystals revealed that they are not true single crystals but rather highly oriented columnar grained structures. The [001] direction is within three to four degrees of the physical z-axis while the columnar grain boundaries are a result of lattice rotation in the x-y plane. It is expected that these crystals will perform ballistically in a manner identical to the monocrystals. The possible use of these columnar crystals in ballistic applications leads to concern as to the ability to launch these as penetrators and how a sabot would be constructed. A third flow-anisotropy may provide a solution. In this effort the fabrication of tungsten single crystal whiskers with dimensions of approximately 10 microns across by one millimeter long is being investigated. These whiskers are envisioned to be processed with binders, like heavy alloys, and oriented during processing so as to place the whisker parallel to the long axis of the penetrator. The heavy alloy binders will provide strength and ductility for launch and sabot design while a high loading of the single crystal whiskers will provide the flow anisotropy desired. Lastly, a hybrid approach is being considered where the single crystal whiskers may be bound together with a binder that exhibits adiabatic shear tendencies.

Nuclear Munitions Prototyping

Over a period in excess of thirty years, between approximately 1958 and 1990, Watertown provided a continuous series of engineering support and prototype development services to the Program Manager for Nuclear Munitions (PM-NUC) headquartered at Picatinny Arsenal. These services ranged from conducting design analyses of developmental nuclear projectiles to the manufacture of prototype components, projectiles and accessories for the testing of both experimental and fielded munitions. It was because of these kinds of support activities that Watertown acquired, through PM-NUC backing, its unique facilities for processing depleted uranium, beryllium and other materials critical to nuclear munitions development. During this entire period several hundreds of thousands of dollars were provided to Watertown by PM-NUC each year to support its various programs. Four typical programs conducted by Watertown are described:

Failure and Redesign of the T-5096 Nuclear Projectile: In the early 1960s it was noted that shell bodies were cracking during

storage of the 155mm round. Cracks occurred at pinned joints between the depleted uranium center shell body and its mating titanium rear and forward shell body pieces. Metallurgical analysis and mechanical testing determined the cause to be stress corrosion cracking of the DU brought about by high residual stresses in the pinned joint. Extensive structural analysis enabled a redesign of the joint to eliminate the residual stresses and to redistribute the high loads experienced during launch. Subsequent firing tests verified the efficacy of the redesign, and a major reliability issues was overcome.

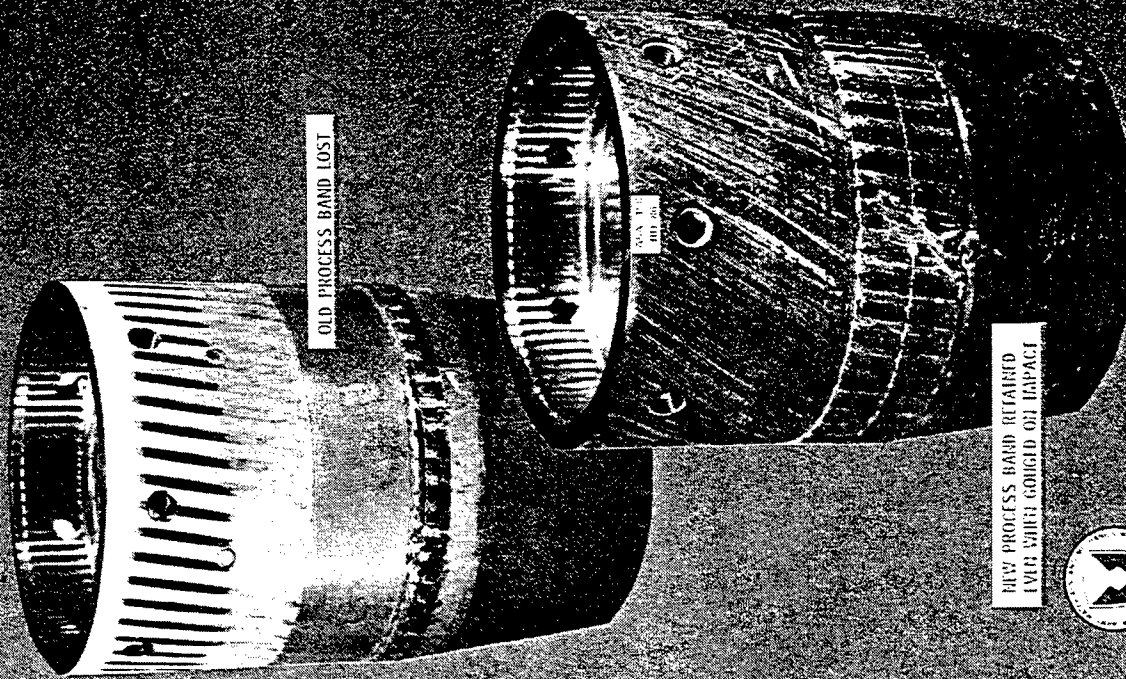
Rotating Band on the XM-785 Nuclear Projectile: During firing tests of this 155mm projectile it was noted that the copper rotating band was separating from the titanium shell body in several pieces, causing variance in the accuracy of the round and posing a threat from the rotating band fragments to personnel who might be positioned immediately forward of the gun. Design constraints required that the rotating band be metallurgically bonded in a shallow circumferential groove in the titanium body rather than swaging the copper band into a much deeper groove as was customary.

It was determined at Watertown that the planned process of hot isostatic pressing the copper band to the titanium shell resulted in the formation of brittle intermetallic phases at the interface which would fracture during launch. A study of alloy phase diagrams disclosed that the element columbium was the only material to exhibit a significant range of solubility (i.e., alloy forming ability) for both copper and titanium. It was proposed that a thin layer of columbium interposed between the copper and titanium would eliminate the brittle intermetallic phases. Watertown developed the process for producing the optimum diffusion bond using a columbium interlayer, and the problem was solved. This material selection and process approach developed by Watertown was critical to the success of this munitions program and was recognized by an Army R&D Achievement Award.

Forging of Titanium Fuse Components: Harry Diamond Laboratories (HDL) in Adelphi, MD was responsible for providing fuses for a special purpose artillery shell under development in the early 1980s. It was determined that commercial suppliers of titanium forgings needed for the fuse components could not meet the stringent schedule and cost requirements for this effort. Watertown was approached to establish an in-house forging capability to meet this need.

This required the design and fabrication of the necessary dies and associated tooling to carry out this near-net shape closed-die forging operation. After developing the optimum forging process for meeting prescribed mechanical property and dimensional requirements, approximately 200 each of five

IMPROVED BONDING OF COPPER ROTATING BANDS TO TITANIUM ARTILLERY SHELLS

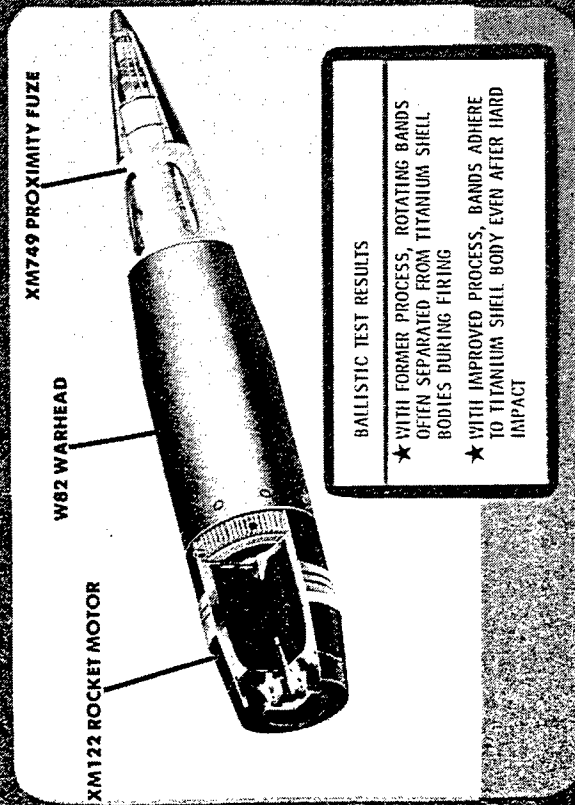


OLD PROCESS BAND LOST

NEW PROCESS BAND RETAINED
EVEN WHEN GOULD ON IMPACT



NEW PROCESS BAND ADHERING EVEN
WHEN SHELL IS FRACTURED ON IMPACT



BALLISTIC TEST RESULTS

- ★ WITH FORMER PROCESS, ROTATING BANDS OFTEN SEPARATED FROM TITANIUM SHELL BODIES DURING FIRING
- ★ WITH IMPROVED PROCESS, BANDS ADHERE TO TITANIUM SHELL BODY EVEN AFTER HARD IMPACT

155 MM NUCLEAR ARTILLERY

different forgings making up the fuse assembly were produced each month for over three years in order to keep this shell development program on schedule and within cost.

Rapid Prototyping of M454 Test Projectiles: The full complement of Watertown prototyping capabilities were brought to bear on the urgent production of T5119 and T5106 test projectiles simulating the M454 nuclear round in 1988-89. A Foreign Military Sales order hinged on establishing the compatibility of the M454 round with the German M109AG3 gun tube. A very narrow window of suitable ballistic range time was available at a European test facility for performing necessary test firings, and test projectiles had to be delivered on an extremely tight schedule. With little advance notice from PM-NUC, Watertown was able to process and manufacture all the components for the test projectiles and to deliver the requisite number of rounds in two-thirds the time it had initially estimated.

Prevention of Gun Tube Failures

A persistent concern of the Army has been gun tube failures, especially those resulting from fatigue cracks on bore surfaces. In the initial rounds of firing, cannon often develop such cracks, a phenomenon also known as heat checking. Cyclic loading extends these cracks, the rate of propagation being affected by such factors as gun design, the type of material used and its thermal history, and the service experience of the gun. Tube failures occur when repeated firing causes crack propagation to attain critical lengths, resulting in fractures.

When prolonged cyclic-loading culminated in cannon failures during World War II, WAL became the first U.S. facility to endeavor to detect and record bore cracks by non-destructive methods. As a result of the laboratories' investigative activities, the Magnetic Recording Borescope (MRB) was developed. The MRB detects and locates surface and near-surface discontinuities, thus identifying fatigue cracks. The cannon tube is first magnetized, then a rotating magnetic tape reproduction head is employed to detect the magnetic leakage associated with a discontinuity.

An early 175-mm cannon tube mounted on an M107 vehicle experienced a catastrophic failure in 1966 during the Vietnam War, causing a severe "limited-service" policy to be imposed, which in turn, presented a serious logistics problem for the Army. In order to detect firing-induced fatigue cracks, a means needed to be developed which would go beyond the then existing non-destructive testing capabilities to examine not only the smooth-bore chamber but also the rifled portion of the tube. Meeting the challenge, AMMRC began an immediate reassessment of the MRB approach, followed by the development of a new scanning

system for the inspection of the entire critical area of the 175-mm gun tube.

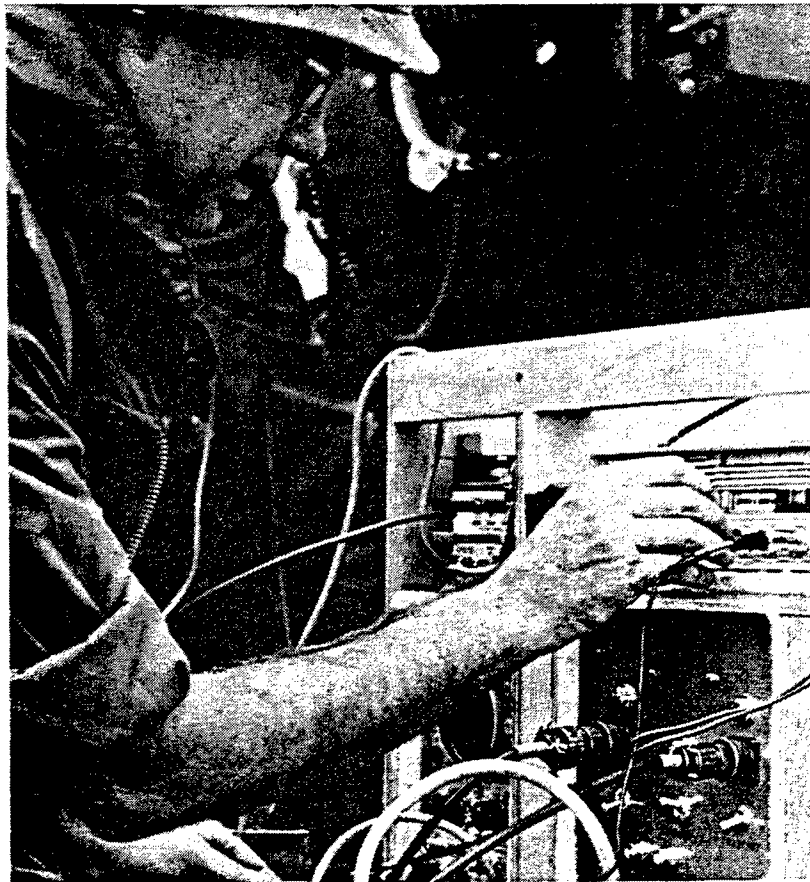
In addition to improvements in detection methods, a concentrated test program was conducted by AMRA in 1967 in an attempt to determine the characteristics and optimum properties for the production of 175-mm gun tubes. Several gun tubes from the Watervliet Arsenal fatigue program were brought to AMRA and were subjected to extensive mechanical tests and metallurgical examinations. The large variation in tensile properties, particularly the reduction of area, was found to be associated with the residual dendritic macrostructure present in some of the steel tubes.

Complete Charpy impact curves were determined at AMRA from segments that were supplied by Watervliet Arsenal. Earlier service cases had established that if it is not possible to process the gun tubes so that the brittle-to-ductile transition temperature is below the service temperature, it is highly probable that some of the gun tubes will fail by a brittle or partly brittle fracture mode. The high tensile strength required in 175-mm gun tubes had necessitated heat treatments in the temperature range where temper embrittlement was a problem. Those tubes tempered for a long time below 1020°F had very high brittle-to-ductile transition temperatures, namely, 105° to 300°F. Specimens which were heat-treated according to optimum practices had transition temperatures in the region of 32° to 68°F. Tests for hydrogen embrittlement gave positive indications, and some of the gun tubes were suspected of crack growth by other than hydraulic fatigue or firing cycles. It appeared that the chromium plating process had a pronounced detrimental effect on gun tube life. The study yielded a more adequate specification for heat treated-to-strength forgings for 175-mm gun tubes. Forgings were then produced having toughness characteristics far superior to those of earlier gun tubes.

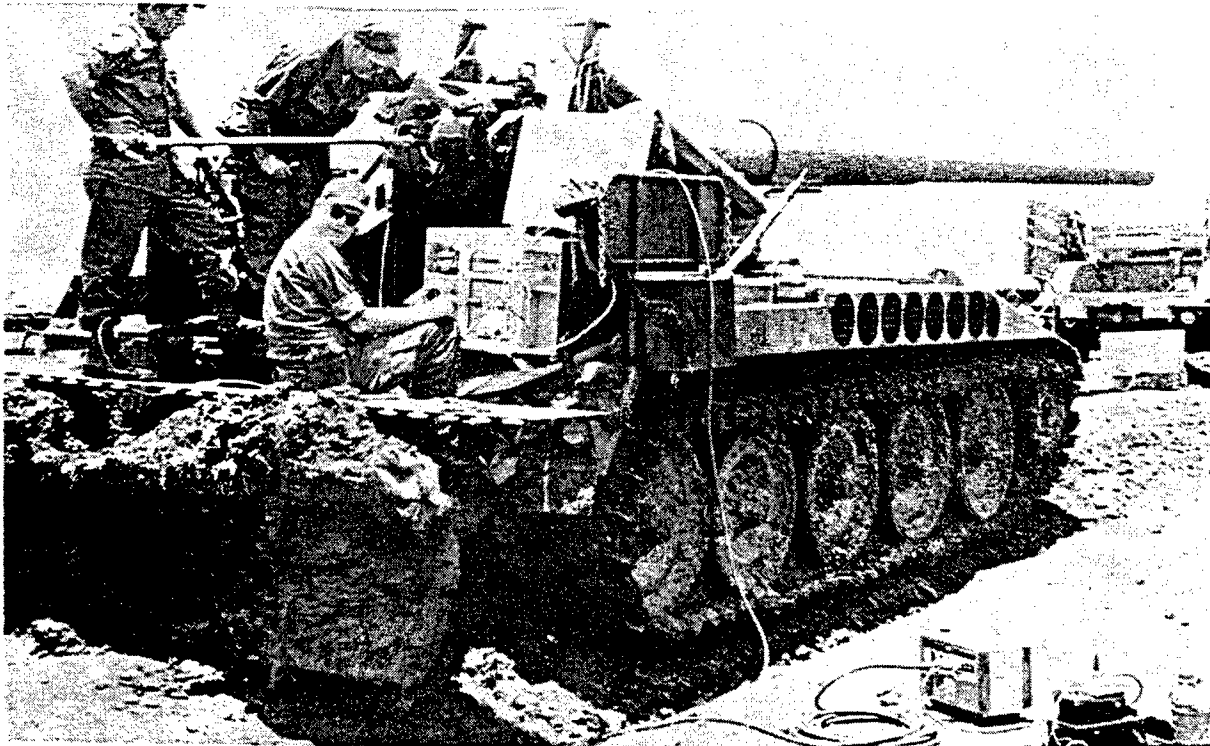
Because of the need to verify the performance of the production autofrettaged 175-mm M113 E1 gun tube under actual service conditions and to obtain a larger sample, a Special Test for Service Life was planned for implementation in Vietnam during 1969. With the MRB having already had its reliability proven, the focus in April 1969 was on the major modifications necessary to provide a MRB system for field use in a combat area and to meet the new requirements of the Special Test.

Actual implementation of the Special Test involved firing a total of twelve tubes, representing three different forging suppliers, to a predetermined wear limit. Throughout the program the MRB testing portion was coordinated and conducted concurrently with the Watervliet Arsenal inspections. At no point in the entire firing schedule were significant fatigue cracks detected in any tube at the attainment of the wear accuracy limit. Building on the technological accomplishments of earlier Watertown researchers, and working closely with other Army facilities, AMMRC was able to provide the Army with the metallurgical and non-destructive testing capabilities necessary

A



B



AMC team comprised of Watertown and Watervliet personnel at a fire-base in Vietnam using the magnetic recording borescope to inspect a 175mm gun.

to restore confidence in, and to improve and make use of, 175-mm guns under combat conditions.

The state-of-the-art potentialities of the MRB were acknowledged in a January 1971 Aberdeen Proving Ground evaluation study which concluded that the MRB outperformed both ultrasonic and black-light borescope inspection methods. The success in using the Magnetic Recording Borescope to monitor progressive fatigue damage in 175-mm gun tubes quickly resulted in the initiation of a Materials Testing Technology Program two phase project with the objective of extending the MRB capability to other caliber gun tubes.

Laboratory and field testing, constant modification and extension of technology, successfully combined in the various phases of the MRB programs to produce a clearly improved non-destructive testing mechanism. In turn, the MRB advances were utilized in conjunction with existing test modes such as the Charpy impact test to come up with better metals processing techniques for gun tubes, furthering Army objectives of combat readiness, troop safety and materials research for military applications.

Ceramic Gun Barrel Liners

Early work on ceramic gun barrel liners was conducted in 1976 by Maremont (Saco, ME), where a silicon carbide lined gun barrel module was successfully fired in a single shot mode for one thousand rounds without indication of failure. This program was sponsored by the Large Caliber Weapons Laboratory of AMCCOM, Picatinny Arsenal (ARRADCOM), New Jersey. The results of this program were sufficiently promising to interest MTL in pursuing the idea of a ceramic liner for gun barrels. At this time, Stellite liners had been very successful in reducing wear and erosion problems in small caliber rapid fire weapons. However, Stellite is rich in cobalt, an expensive and critical element. Consequently, an alternative material without strategic elements was desirable. Ceramic materials generally contain no critical or strategic materials and can be extremely wear resistant at high temperatures. Therefore, the prospect of using ceramic materials as liners in gun barrels appeared promising in light of the preliminary results with silicon carbide.

MTL contracted Maremont, which later became Saco Defense Incorporated, in 1981 to test fire a glass matrix composite reinforced with graphite fibers. This material survived the single shot test procedure but excessive wear caused the test to be terminated at under 100 rounds. Attempts to duplicate the silicon carbide results presented a situation that was not anticipated. The silicon carbide liners would show circumferential cracks at about one quarter inch from the muzzle end of the barrel after only one shot. After an extensive study, which included finite element analysis and fractographic

analysis, it was determined that machining of the outside surface was very critical and that the roundness and a high surface finish must be maintained. It was also during this time that the ability to produce rifling in the ceramic material was accomplished by ultrasonic machining. Although MTL had a rifled sample made, all the test firing was conducted on smooth bore liners.

In 1983, with combined support from MTL and the Defense Advanced Technology Laboratory (DARPA), Saco Defense, Inc. was contracted to conduct tests on four ceramic materials as potential gun barrel ceramic liner materials. The ceramic materials chosen included silicon carbide, sintered silicon nitride, partially stabilized zirconia and sialon. These represented materials readily available, and published mechanical and physical property measurements on the hardness, flexural strength, fracture toughness, thermal expansion, etc. were considered in their selection.

In the course of this study, a finite element analysis was developed to evaluate the stresses on the ceramic liner due to the shrink fitting process that was required to test the material in a gun barrel. Also developed in this program was the use of a dynamic test apparatus where the pressure at rupture for the material under test was determined under gun operating conditions without the benefit of any reinforcing sleeve. These procedures were established so that a rough screening process could be developed to determine how a material would stand up to the test firing. Ironically, the best screening process turned out to be the actual single shot test firing of the ceramic lined gun barrel module.

The three ceramic materials that survived the 1000 single shot test firing were the silicon carbide, silicon nitride, and the sialon material. In 1984, DARPA continued its support of this program, and a multiple fire testing program was developed for two down selected materials which were silicon carbide and sialon. The test procedure for this phase utilized the same configuration of the liner as in the single shot test. A Browning M2-HB machine gun was modified to accept the ceramic lined test modules. The test firing was comprised of incremental burst firing of groups of five rounds up to fifty, then groups of ten rounds (i.e., 5, 10, 15, ...50, 60, 70 ...etc.) to 100 rounds and finally the groups were increased to 25. These burst firing rounds were accumulated on each individual test module. The silicon carbide performed the best of the three and survived a burst fire mode of 125 rounds after which a crack in the liner was observed and testing was terminated. The sialon survived up to 90 burst fire rounds. Prior to the multiple firing procedure, each test module was single shot tested to 1000 rounds. The silicon carbide survived 1000 rounds single shot and a total of 800 burst fire rounds which included a maximum burst fire of 125 rounds under a firing rate of 670 rounds per minute.

After this program, Saco Defense, Inc., with funding from the Advanced Research Projects Office (ARPA), developed a 20mm

ceramic lined gun barrel which incorporated a silicon carbide liner. Under significantly higher thermal conditions, the liner was tested and experienced some limited success, although failure in the form of cracks was observed.

These programs would appear to answer the question of whether a ceramic liner can be effective in a gun barrel environment to reduce wear and erosion. Throughout these tests, very little wear and erosion was observed, and the primary concern with all the engineering involved was to prevent failure of the ceramic material. It would appear that gun designers will be able to include ceramic liners, especially when higher flame temperature propellants are required to increase the accuracy, range and fire power of future armament.

Intumescent Materials

The primary contributor to the vulnerability of the M-109, 155mm self-propelled howitzer is on-board ammunition. If struck by a high velocity projectile or shaped charge jet, unprotected bags of propellant in a howitzer will ignite and spread heat and flames to surrounding propellant bags, causing them to ignite also. This phenomenon, loosely called fratricide, could prove fatal to both crew and vehicle in less than a minute.

As part of the ARDEC-sponsored program to modify and to improve the M-109, researchers at MTL undertook a study in 1989 of propellant storage aboard the howitzer. The objective of this effort, with the proposed compartmentalization concept as a point of departure, was a study of what measures might effectively increase system survivability and personnel safety by limiting or preventing, fratricide of stored propellant when attacked by a shaped charge threat. This included a determination of candidate structural materials within which the propellant charges could be housed, particularly materials which might serve to thermally insulate stored rounds from each other.

The MTL team explored the possibility of protecting propellant bags by storing them in individual cylindrical sleeves. Initially, they looked for weight savings by comparing the performance of composite materials to sleeves made of steel or aluminum. Then they began wrapping all of these sleeves in intumescent materials to see if fratricide could be prevented. An intumescent material is one which swells when exposed to a high heat source such as an open flame. The endothermic process accompanying intumescence as well as the formation of a char layer provide insulative protection of the substrata from the heat source.

Propellant detonation testing yielded clearly impressive results. The propellant in the unprotected sleeve always burned, igniting each time in approximately 11 seconds, and the sleeves, except for those made of steel, either ruptured or burned through. On the other hand, the propellant in the protected

sleeve never ignited, and the sleeves themselves were in most instances virtually unscathed. Thus, where intumescent agents were used, fraticide was prevented.

The heat inside the protected sleeves, as measured by "tempi-labels" never rose above 200°F, the lowest value measurable with this technique. This finding was deemed of great importance, because, even if the propellant does not come in contact with the flames, heat in excess of this range could cause ignition.

In the second type of test, more specific quantitative data were sought as to the difference in heat flow through a metallic plate when protected vs. not protected by a layer of the intumescent material. These data are useful and needed by designers seeking to exploit the flame-retardant properties of such materials. It was discovered that the propellants under consideration have a time-at-temperature dependence of the auto-ignition temperature. Most can tolerate 350°F for 10 minutes, but auto-ignition occurs after only 10 seconds exposure to 500°F. By placing intumescent materials between the flame and the metal, the temperatures on the unexposed side of the metal sheets--the side that would touch the propellant--were dramatically lowered in comparison to those temperatures charted for unprotected metals in the experiment.

The results of the program showed that lightweight fiber-reinforced composite cylinders can be used to store propellant charges. Further, it was proven that two commercially available materials, INTERAM and to a somewhat lesser extent, EYPEL A, are effective in preventing propellant fraticide. One tremendously important aspect of this effort is the fact that the fire protective materials identified in this program can be employed in the M-109, the M-548 cargo carrier which is used to resupply munitions to the M-109 in the field, and practically any member of the armored family of vehicles where propellant protection is required. The efficacy and simplicity of the fire protection concept makes it possible to incorporate that concept within currently fielded Army combat vehicles almost without modification. As an additional benefit, the fire protective materials can be applied to the protection of munitions during transport between any two locations and in practically any configuration. By discovering that intumescent materials prevent fraticide, MTL researchers provided the technology application both to save the lives of soldiers and to increase system survivability.

HAWK Missile System

Assistance provided by Watertown Arsenal Laboratories to the U.S. Army Missile Command and their contractor, the Missile System Division of Raytheon Company, is a unique example of long term continuing cooperation with the commodity commands by an

Army laboratory. Raytheon Company was the prime contractor for the HAWK missile system, designed to provide air defense against enemy air attack. Much of the development work and manufacturing was being carried out by Raytheon in plants in the Boston area, particularly Andover, MA. In August 1960, during a routine inspection at Red River Army Depot, where a number of the completed missiles were being stored, it was observed that a HAWK missile gas cylinder, pressurized with nitrogen gas, had exploded. The Missile Command, through the HAWK System Field Office at the plant in Andover, requested immediate assistance from WAL personnel to determine the cause and extent of the problem.

Assistance was provided, and a rapid and thorough investigation was carried out. It was demonstrated that this was a stress corrosion failure, that the material of the gas cylinder was not the optimum choice, and that future failures could be anticipated. Within three weeks a second, similar failure occurred. Working with materials people at the contractor, Arsenal personnel made recommendations for a new, tougher steel, as well as improved processing and inspection procedures. These were successfully implemented, and the immediate problem of the field failures was eliminated.

The geographic proximity of the Watertown site to the contractor, as well as the depth and excellence of the materials knowledge provided by the Arsenal personnel, resulted in a close working relationship between the HAWK System Field Office, the Raytheon Company, and the Watertown Arsenal Laboratories (later AMRA and then AMMRC) through the years. As in any complex manufacturing operation, a number of production problems arose during the next 16 years. These involved such matters as heat treatment of the gas cylinder, oil dome, and other components, brazing and welding problems, forming, and non-destructive inspection. In several cases, rejection rates were so high that there was danger of shutting down the entire production line. In most cases, after a telephone request from the HAWK System Field Office, same day service could be provided. This could involve short consulting sessions, visits to the production facilities on site or at a subcontractor, or a longer laboratory investigation back at Watertown.

These sessions were generally informal, and while fully documented by trip reports, telephone memos, etc., did not involve any formal contract with Watertown Arsenal Laboratories or transfer of funds, or unfortunately, awareness by the greater community (Washington and Huntsville) of the important role that AMMRC was playing. Recognizing this, the HAWK System Field Office late in 1975 requested that formal recognition be provided to the then AMMRC for its important contribution through the years. On February 19, 1976, Col. Deadwyler, HAWK Program Manager in Huntsville, AL, at a ceremony in the Bldg. 36 Auditorium, presented a Certificate of Appreciation for Patriotic Civilian Service to AMMRC and another specifically to the Materials Development Laboratory of AMMRC, signed by Maj. Gen.

George E. Turnmeyer, Commander of MILOM, for furnishing outstanding technical and testing support to the HAWK.

Since so many Watertown personnel had contributed during the years, no individual names were used. This citation reflects favorably on the whole laboratory, and is a clear demonstration of the important technical contribution that an R&D laboratory could and did provide to the Army.

The citation reads:

"For furnishing outstanding technical and testing support to the HAWK System Project Managers and the prime contractor, Raytheon Company, analyzing and verifying the high reliability design required for the HAWK System. The positive reaction furnished by Army Materials and Mechanics Research Center, the expertise employed and the solutions attained resulted in major metallurgical improvements to the HAWK System. This dedication of effort in support of a major weapon system development program is in keeping with the highest Army tradition of professionalism and reflects great credit on the Army Materials and Mechanics Research Center, U.S. Army Material Command, and the Department of the Army."

Support of PM CAWS on Copperhead

Copperhead is a 155 mm cannon-launched guided projectile intended for use as an anti-tank weapon. It underwent development and early production at the Aerospace Division of Martin Marietta Corporation in Orlando, FL starting in 1974 and extending into the early 1980s. It is an extremely complex and sophisticated system; and its complexity is perhaps typical of the direction future weapons systems development will take. As a hybrid, it combined some of the advantages and disadvantages of both a missile and a conventional cannon launched projectile. In terms of the electronics and laser guidance features, it resembled other ground-to-ground missile systems, yet the severe launch environment, a 155 mm cannon tube, is that of a conventional artillery projectile, and far more severe than any conventional missile system encounters. Under the most severe launch conditions anticipated, the set back forces could be in excess of 10,000 g's.

The projectile consisted of three major components: a guidance section, containing the laser guidance system; a warhead section, containing a fuse and shaped charge; and finally the control section, consisting of four symmetrically placed wings (for extended range) and four similarly placed fins for control purposes, all carried in the control housing. Since the

projectile was considerably more expensive than conventional projectiles, maintaining a target cost ("design-to-cost") was a significant factor in the development program. Weight of the projectile was also an important consideration. The control housing, produced from high strength 4340 steel, was the component with which AMMRC personnel had the most interaction. Early in the development process cracks had been detected as a result of plasma arc cutting of the wing and fin slots in the heat treated control housing, and cracks were also found in projectiles that had been fired and undergone a soft recovery. In one case cracking was detected in a control housing stored in a laboratory office. As a result of the first problems, AMMRC was requested by the Product Manager for Copperhead in the PM CAWS office at ARRADCOM headquarters at Picatinny Arsenal to provide materials and mechanics assistance to the program. AMMRC personnel participated in Quarterly Reviews throughout the development cycle, participating in the Control Section Working Group meetings, as well as in supporting analytic work back at AMMRC. Assistance and advice was rendered over at least a seven year period extending into the 1980s.

AMMRC assistance was focused on the choice of steel and processing methods for the control housing, and on a fracture mechanics analysis of the component, including a thorough stress analysis, inspection procedures, and verification of the stress analysis by static testing, as well as a redesign of critical areas of the housing. The aircraft quality 4340 steel tubing and forging were friction welded to form the housing. The component was heat treated to an extremely high yield strength level of over 200 ksi, where its fracture toughness was very low. This is a strength level far in excess of what is generally used for the steel in structural applications, especially in cannon launched projectiles. A thorough educational process was necessary to convince the aerospace industry systems- and electronics-oriented personnel at the contractor of the risks attendant to using such a high strength, low toughness and low flaw tolerant material, reinforcing in many cases what their own materials people had been stating. A number of suggestions were made, including changing to an alternate steel such as a maraging steel; using vacuum melted, electro-slag remelted steel, or at least vacuum degassed steel; lowering the strength level to improve toughness; and using a higher purity steel (lower sulfur and phosphorous particularly) than conventional aircraft quality steel. Constrained by cost, scheduling, and design constraints, the recommendations were only partially accepted.

The control housing is an extremely interesting component. It undergoes primarily compression loading as a result of set back forces during launch. Only a simplified stress analysis had been done by the contractor, ignoring stress concentrations at section changes and the influence of the wing and fin slots. Under the leadership of Mr. Joseph Bluhm of AMMRC, a complete stress analysis was finally carried out, which identified the critical areas and revealed the presence of rather high tensile

stress at irregularities in this predominantly compressive environment. A redesign was then proposed, and carried out, to lower stresses at critical areas such as keyways, etc. From the stress analysis, the mechanical properties of the steel (fracture toughness) and the worst case scenario of the loads, a crack-inspection map (CIMAP) was developed, which provided a three dimensional map of the critical flaw size at every location. This was a major accomplishment. The CIMAP was necessary to develop a non-destructive inspection procedure, identifying the most critical areas and flaw size where the critical flaw size was smallest, and thus where inspection should be concentrated.

Verification of the stress analysis by laboratory tests is an important part of any stress analysis. This was a particularly severe problem for a cannon launched projectile because of the nature of the loading in service, and the fact that the expected worst-case service environment is not always well defined. A major part of the stress arises from the high set back forces during launch. These are a function of the mass of the projectile forward of a given section, and are a maximum at the rear end of the projectile, which sees the effect of the entire projectile weight. The result is that it is difficult, and even impossible, to simulate the set back effects in a static test on a full length projectile in a tension-compression machine. The load necessary to proof the back of the projectile is far in excess of what is required to cause yielding and failure of sections further forward. Working with personnel at the Waterway Experimental Station at Vicksburg, MS and using their 2400 KIP testing machine (which had been transferred from Watertown Arsenal on its closing in 1967!), as well as Martin Marietta personnel, Mr. Bluhm was able to develop a test procedure to simulate the loading on short sections of the housing, thus verifying the stress analysis at critical locations in the control housing.

A number of other areas were investigated at AMMRC as well. These included, among others, efforts to develop and evaluate improved obturator materials, a laboratory investigation of the stress corrosion cracking behavior of the control housing steel, and improved heat treatment and processing of aluminum and other alloys used in various components.

The assistance that AMMRC provided extended over at least a seven year period. The materials and fracture mechanics expertise provided by AMMRC was extremely important, since this represented areas where contractor effort assigned to the program was not always sufficient to anticipate all problems and provide solutions. The AMMRC engineering assistance, and particularly the crack-inspection maps developed by Mr. Bluhm and co-workers, was a significant factor in helping to improve the reliability of this pioneering system.

Patriot Ceramic Radome

Watertown contributed to the development in the early to mid 1980s of the Patriot air defense missile. MTL assisted MICOM and Raytheon, the prime contractor, in evaluating fused silica ceramic materials which were used as the radar dome, or radome, on the Patriot missile. Not only did MTL evaluate the mechanical properties of the fused silica, but it also helped to establish uniformity and property requirements for the ceramic. In addition, a new whisker-reinforced fused silica was created that had significantly enhanced toughness and rain erosion resistance. Finally, MTL assisted with several failure analyses during the prototype evaluation phase. Critical problems in radome manufacture were identified which enabled Raytheon to take remedial action, with the result that the radomes became very reliable in production.

ENGINES AND AIRCRAFT

Engine Ceramics

AMMRC's Role in Developing Silicon Nitride Ceramics for Engine Technology

Since the invention of the diesel engine by Rudolph Diesel in the 1890s and the development of the earliest gas turbine engines in the first decade of the twentieth century, it has been recognized that ceramics would be ideal materials for use in such devices. Ceramics maintain their strength and wear resistance to higher temperatures than do metallic alloys. They are both more corrosion and erosion resistant than metals, and are much lighter. However, these advantages of ceramics were canceled by the overwhelming negative characteristic of ceramics, namely their brittleness. This often leads to catastrophic failure when ceramic components are subjected to large tensile stresses or rapid and large temperature fluctuations (this is referred to as thermal shock).

The efficiency and military performance characteristics of gas turbine engines increase as the maximum operating temperature increases. By the late 1960s it became apparent that the upper limit of high temperature metal alloy development for gas turbine application was near. Further, in order to operate at higher temperatures additional air cooling of turbine components was required, and the point of diminishing returns for this technology was also clearly in sight. Therefore, the DoD's Advanced Research Projects Agency (ARPA) decided that it was important to initiate a major program to see if ceramic technology had advanced to a level where the negative attributes of ceramics could be surmounted and the benefits could be advantageously exploited. Two technological developments of the 1960s provided reasons for optimism. Firstly, advanced computers and computer software for stress analysis could provide the basis for precision design of ceramic components, minimizing the probability of brittle failures. Secondly, new ceramic materials, silicon nitride in particular, were tougher (less brittle) and more thermal shock resistant than previous ceramics.

In the 1970-71 time frame AMMRC was uniquely positioned to play a key role in this new technology. Through AMMRC's participation in the U.S.-U.K.-Canada-Australia-N.Z. Technical Co-operation Program (TTCP), Watertown was aware of the major advances being made in silicon nitride science and technology in the U.K. Indeed, in 1971 Watertown had a TTCP exchange scientist at the Admiralty Materials Laboratory in England, to help transfer this knowledge back to AMMRC. Additionally, at that time AMMRC had the largest ceramics research laboratory in DoD, as well as a significant computer stress analysis capability

within the mechanics laboratory. In recognition of this key combination of competencies, ARPA selected AMMRC to monitor its \$20,000,000 Brittle Materials Design/High Temperature Gas Turbine Program, providing management and technology development input as well as contract monitoring.

During its role as ARPA Program monitor, and in parallel in-house funded core and customer programs AMMRC scientists and engineers made many significant contributions to the development of silicon nitride science and technology. Several of these contributions and achievements are summarized below.

The Yttrium Oxide Additive to Silicon Nitride

Ceramics are typically fabricated into components by making a pre-form of ceramic powders and firing them in a furnace at very high temperatures (e.g., 1800°C) in order to make a fully dense and strong part. This process of high temperature firing and component densification is called sintering. Silicon Nitride, being a covalently bonded compound, is particularly difficult to sinter and it can not attain full density unless a sintering aid or additive is mixed into the starting powder. A major discovery in the U.K. during the mid 1960s was a magnesium oxide additive that formed a grain boundary glass in the silicon nitride during sintering which facilitated both the attainment of full density and high toughness. This material was made under license by a U.S. manufacturer, and its availability was one of the enabling technologies for the ARPA program. However, as experience accumulated it was clear that the magnesium oxide containing glassy grain boundary was limiting the useful temperature of silicon nitride to 1200°C. Since the engine design required a material that could operate for hundreds of hours at temperatures of 1350°C, it was clear that the material had to be improved.

Researchers at AMMRC took the approach of developing a higher temperature glass phase for the grain boundaries that would still facilitate development of full densification, strength and toughness. It was discovered that yttrium oxide could be used as a sintering additive to densify silicon nitride and increase its useful operating temperature beyond 1300°C. In addition, the yttrium oxide containing grain boundary could be crystallized by heat treating, which increased the creep resistance of the material. U.S. Patent 3,830,652 was issued to the AMMRC researcher in 1973 and was licensed to the Norton Co., Ford Motor Co., Westinghouse Corp, and others. This patent and related papers laid the foundation for worldwide development of yttrium oxide containing silicon nitride materials. These yttrium oxide containing ceramics are now commercially used in applications such as turbocharger rotors, diesel engine components, ball bearings, and cutting tools. The annual value of silicon nitride cutting tools deriving from this invention is

estimated to exceed \$50,000,000 per year.

Gas Pressure Sintering of Silicon Nitride

Silicon nitride is not a stable compound. Above about 1800°C it starts to dissociate into nitrogen and silicon gases. However, in order to sinter silicon nitride to full densities one must process at temperatures above 1800°C. This poses an obvious dilemma. One way to resolve the dilemma is to hot press, which was the technique used in the work described in the proceeding paragraph. Hot pressing is expensive and can only produce rather simple shapes such as plates and cylinders. Gas turbines require very complex shaped and curved parts such as blades and vanes. To make these parts a die-less sintering technique was required. Attainment of such a technology for making fully dense, net shaped parts without a die eluded the industry until researchers at AMMRC demonstrated that sintering in a nitrogen gas overpressure would work. AMMRC, both on contract to GE and in-house, amplified this concept to include a two-step gas overpressure sintering sequence. This two-step sequence used a relatively low overpressure of several atmospheres of nitrogen to sinter the silicon nitride component to the point where the surface porosity was sealed. At this point the gas pressure of the nitrogen in the furnace was increased to approximately 100 atmospheres and the component was fully densified without a die to near-net shape. This technology has been utilized to make most silicon nitride turbocharger rotors in the world. At one point in the mid 1980s eight furnace manufacturers in the U.S. and overseas sold commercial furnaces for sintering silicon nitride ceramics by this method. While no patents were issued in this area, AMMRC's innovations are well documented in the technical literature.

Control of the Nitridation of Silicon by Nitrogen Demand

One of the principal industrial processes for synthesizing silicon nitride powders, as well as reaction bonded silicon nitride pre-forms for subsequent densification by gas pressure sintering, is the direct nitridation of silicon powder. In this process a great deal of heat is released. If the process is not closely controlled this heat release can be large enough to melt the silicon and ruin the product, or in the worst case ruin the furnace (a very costly event!). Researchers at AMMRC devised a control methodology to assure that such run away reactions could not occur. By not allowing additional nitrogen to enter the reaction chamber while the temperature was still increasing, the problem was overcome. While this sounds simple in hindsight, the realization of the concept under the aggressive temperatures and

environments of a tightly sealed 1400°C reaction chamber was indeed a major accomplishment. It has become standard industrial practice to use this technique, or derivatives of it, for all commercial silicon nitridation facilities.

AMMRC's Role in "Adiabatic" Diesel Engine Technology

Since the mid 1970s the U.S. Army Tank and Automotive command has had a significant interest in developing low heat rejection, turbocompound engines (the so called "Adiabatic" engine). This engine would be significantly smaller for a given horsepower, much more fuel efficient, have fewer parts, no water cooling, and be more survivable on the battlefield. To run with no cooling means that some ceramic components will be required. In 1978-79 the Cummins Engine Company, under contract to the Army, was to demonstrate the feasibility of such an engine by running a ceramic configured single-cylinder uncooled diesel engine.

With only about six months remaining on the contract it became clear to both TACOM and Cummins that none of the commercial silicon nitride piston caps that they had procured from U.S. or foreign sources would make it through the required 250 hour engine test. Because TACOM was aware of AMMRC's expertise in ceramic processing, silicon nitride technology and ceramic design experience, they funded a "crash" program at AMMRC to fabricate and deliver parts to their contractor, Cummins. AMMRC engineers recommended slight design changes to the piston cap. Cummins provided specially configured graphite tooling on a rapid turn around basis, and AMMRC fabricated a series of piston caps to near-net shape, delivering them to Cummins in three months. One of these caps was run in the engine demonstration for the required 250 hours. The only piston cap to successfully make it through proof testing and a full engine test was fabricated at AMMRC. As a result of this successful test, enabled by AMMRC technology, TACOM proceeded with their low heat rejection engine technology programs and some silicon nitride components are likely to be in future Army diesel engines. The fact that only AMMRC could fabricate a successful piston cap circa 1979 is an indication of the Laboratory's global forefront position in silicon nitride technology at that time.

High Temperature, High Performance Gear and Bearing Materials for Helicopters

By the 1960s helicopters had increased their power and their maneuverability to such an extent that greatly increased stresses and operating conditions were being imposed on main drive systems. The helicopter fleet in Vietnam was often called upon

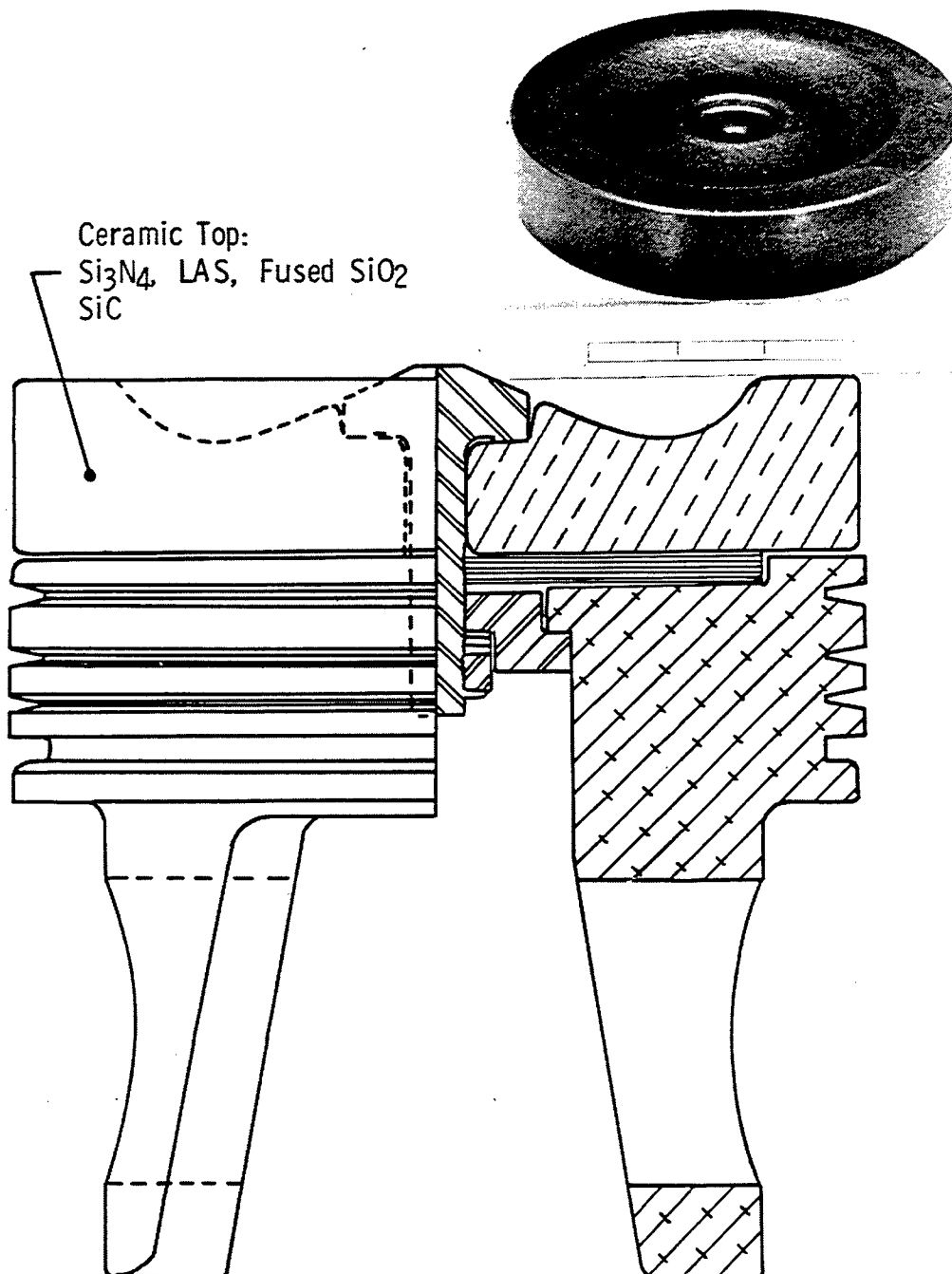
to exceed prescribed speed and maneuvering envelopes by wide margins, causing increased failure rates in transmission gears. Moreover, helicopters under development were being designed to operate at still higher speeds under more severe conditions, i.e., higher temperatures, placing increasingly stringent demands on gear and bearing steels. In addition, there was imposed a requirement for limited operation under oil starvation conditions, if the transmission were to be damaged by hostile action.

The workhorse steel used in the manufacture of high performance gears for helicopters had been vacuum processed AISI9310. This tough low carbon alloy steel was carburized to obtain high surface hardness and heat treated to achieve good core toughness. The shortcoming of AISI9310 exposed by the increased demands for higher performance was its loss of strength after exposure to higher operating temperatures anticipated in modern helicopters, which could even exceed the tempering temperature of the steel, 300°F. While improvements in lubricants and lubricating systems helped to mitigate this deficiency, the need of gear materials with higher temperature capabilities remained evident.

Watertown scientists worked closely with Boeing Helicopter Company, producer of the CH47 Chinook helicopter, to introduce modified tool steels as potential high performance gear materials. Tool steels are known generally to retain their hardness to higher temperatures than AISI9310 or other structural alloy steels but possess inferior fracture toughness, making them more susceptible to brittle fracture. Consequently, close attention had to be paid to preserving adequate fracture toughness to avoid catastrophic failure, particularly in the flange and other areas where the core material served as a structural element. Under joint Army/Navy sponsorship, Boeing, together with Teledyne-Vasco, developed a carburizing grade of tool steel called VASCO X-2, which was evaluated extensively at Watertown in competition with other alloys. Optimum processing of VASCO X-2 and other steels was investigated, such as the use of double vacuum melting (VIM-VAR) and optimization of the carbon content range, as well as vacuum carburizing, with the goal of balancing high temperature tribological properties in the carburized case with adequate fracture toughness properties in the core of the gear.

Another alloy receiving thorough evaluation was CARTECH X-53, a modified tool steel developed independently by Carpenter Steel Company. Watertown provided technical support to the Aviation Systems Command on several contractual efforts on process development of these candidate high temperature carburizing grade tool steels. Although CARTECH X-53 proved to be a fully acceptable choice for high performance gears, the much larger data base and experience base with VASCO X-2 led ultimately to the latter's selection for use in the 70's version of the CH47 Chinook helicopter.

In an effort to further improve the core fracture toughness



The ceramic piston cap for the adiabatic diesel engine, and how it attaches to the piston.

of these secondary hardening carburizing grades, Watertown later sponsored an alloy development program with Climax Molybdenum. This work resulted in a new alloy, designated Amax B in the final report, that was subsequently renamed MTL-2.

In the bearing area General Electric had undertaken extensive evaluation and development of similar alloys. The principal turbine engine main shaft bearing steel, M50, a through hardening steel, had reached the limit of its performance capabilities through a number of processing improvements. At the even higher operating speeds and loads for new engines it was determined that the much higher core toughness of carburizing steels was necessary. In this work a modified low carbon version of M50 with some nickel was developed. This new grade was designated M50NiL, and is now flying in both military and commercial engines. In this same (GE) program an electrolytically deposited coating, known as thin dense chrome, was also thoroughly evaluated. A considerable improvement in bearing life tests was noted. This began the development and evaluation at Watertown of emerging coatings. The Rolling Contact Fatigue (RCF) properties of a number of coatings were evaluated, including: thin dense chrome, ion beam assisted deposition of titanium nitride, ion plated zirconium nitride and hafnium nitride with and without additional chrome plating, and diamond-like coatings.

It has been found through long experience that the corrosion of bearings is an important factor in their service life. Corrosion results in small pits and subsequent micro-spalling in rolling contact fatigue. This has proven to be particularly detrimental in military systems that often operate in severe environments and which may have longer downtimes between missions. The bearings with the coatings mentioned above have shown improved corrosion resistance. A further advance has recently been made with the development of a stainless carburizing alloy. The alloy made by Carpenter Technology has been designated Pyrowear 675. At Watertown RCF measurements have been completed on samples with four different carburizing/heat treatment cycles. This alloy is now beginning to find application in helicopter gearing.

Other activities in the bearing area have included RCF studies on powder metallurgy tool steels produced by Crucible Materials Corp. This work was done in collaboration with Syracuse University. Also studies were completed on silicon nitride bearing material tested both with ceramic and steel balls. Very large performance increases have been demonstrated and hybrid bearings (carburized steel race with ceramic balls) are being applied to the Integrated High Performance Turbine Engine Technology (IHPTET) demonstrator engines.

Titanium Castings

Casting has always been an attractive process for producing

a complex part to near-net shape. In the mid 1970s there was a strong incentive to develop technology to produce high-quality titanium castings for fatigue-limited applications to take advantage of this near-net shape capability. At that time parts for such applications were machined from titanium forgings because state-of-the-art titanium castings had fatigue properties significantly below those of forgings (endurance strengths of 20 to 30 ksi for castings versus 60 to 80 ksi for forgings) due to porosity (typical of castings) and surface contamination (titanium is very reactive, absorbing impurities from the mold). Machining parts from forgings, however, was expensive not only because of the intrinsic cost of machining, but also because most of the forging was discarded as chips (up to 95% of the forging in extreme cases), and titanium was costly at that time (\$15 to \$20 per pound).

In addition to this incentive there were two technological developments, improved investment casting and hot isostatic pressing (HIP processing), which had the potential to overcome the basic difficulties with surface contamination and porosity in cast titanium. In investment casting a wax pattern, which can be very complex, is coated (invested) with layers of ceramic. The invested pattern is then heated to a high temperature which cures the ceramic and melts/vaporizes the wax, leaving a cavity the exact shape of the pattern. In the mid 1970s recent advances in investment composition permitted the casting of titanium with minimal surface contamination. In the other development, HIP processing, a part is heated to a high temperature in an inert gas under high pressure. This treatment collapses and welds shut porosity. Watertown with M & T funding from the Aviation Command (see Technology Transfer for a description of the M & T program) conducted two consecutive programs to use investment casting followed by HIP processing to develop titanium casting technology for fatigue-limited rotating parts for aircraft.

The first program, conducted in the late 1970s, focused on the Titan 62T-40 Auxiliary Power Unit (APU) manufactured by Solar Turbines International. An APU is a small gas turbine engine which supplies electric power to a military system independent of the main engine. Three major systems used the Titan APU: the Army's Blackhawk helicopter; the Air Force's F16 aircraft; and the Navy's LAMPS helicopter. It contains fatigue-limited rotating parts, but it is not flight critical, i.e., if the unit failed the aircraft could land safely. This application therefore was considered to be an optimal entry point for introduction of new technology.

The part selected for the program was the compressor impeller which weighed 2.6 pounds. It was machined from a 22 pound pancake forging. This generated 19.4 pounds of chips, with a finished part cost of \$2200. Solar carried out the program under contract to Watertown. The mold was produced using the investment process. The casting of the Ti-6Al-4V alloy was done under vacuum and the mold spun centrifugally to insure mold filling. The casting was chemically milled to remove 5 mils from

the surface, HIP processed at 1650°F at 1500 psi for 2 hours, and then heat treated.

The program was very successful. Spin testing of the cast impeller demonstrated that it met all requirements. This was followed by testing in an actual engine. The cast impeller performed according to specification in over 280 hours of operation with over 100 start/stop cycles. The cost of the completed impeller in production quantities was projected at \$860 or 60% savings over the conventional forged and machined impeller.

After successful completion of the APU impeller program, Watertown and the Army Aviation Command went on to address a flight critical component. The part selected was the damper bracket on the Blackhawk helicopter. The program was carried out by Sikorsky, the manufacturer of the Blackhawk.

Each Blackhawk rotor system contains 4 damper brackets, one per blade. The damper bracket is part of a rotor system designed to counter the effects of ground resonance. The damper bracket is connected on one end to one of the arms of the main rotor hub and on the opposite end to a damper linked to the spindle of the adjacent rotor blade. The bracket rotates with the rotor hub and is subjected to centrifugal and torsional stresses as well as fatigue.

A near-net shape casting offered significant overall savings in material cost and machining time. It would replace a component machined from a 15.9 pound forging to produce an application-ready component weighing 4.2 pounds along with 11.7 pounds of waste chips. The casting produced weighed 6.1 pounds; that was machined to a 4.4 pound component, resulting in only 1.7 pounds of chips.

The damper brackets were again produced from Ti-6Al-4V by vacuum investment casting (without centrifugal spinning) followed by acid cleaning of the surface and HIP processing. To further improve the fatigue properties a beta solution and overaging (beta-STOA) heat treatment was developed. The tensile strength and the high cycle fatigue strength of the cast material exceeded that of the forged material. Full scale testing showed the cast bracket fatigue strength was equivalent to the forged bracket. Machining costs were reduced by nearly 60%. The cast rotor damper bracket was the first titanium casting certified for a flight critical helicopter component.

Thus Watertown working with the Army Aviation Command and the industrial community showed that titanium castings could be technically equivalent to forgings for fatigue sensitive applications in Army aircraft with substantial reductions in machining costs.

Lightweight Aircraft Turbine Engine Protection

Since August of 1988, Watertown has been tasked by the

Federal Aviation Administration (FAA) to evaluate protective materials for containing aircraft turbine engine rotors. Aircraft turbine engine rotor failures are characterized by the release of high energy fragments which threaten both vehicle occupants and vital aircraft systems. The program has focused on investigating the use of lightweight armor material technology as an alternative to traditional steel containment technology.

The first stage of the program involved the development of processing equipment and the fabrication of containment rings from a variety of materials. These cylindrical rings have been made from metal, fiber/resin composites, and hybrid systems consisting of either a metal liner wrapped with a fiber/resin composite or a metal liner wrapped with a dry fabric. The lightweight armor materials investigated were: titanium (6Al-4V), fiberglass/polyester, fiberglass/phenolic, Kevlar/phenolic, fiberglass/polyester-steel, fiberglass/phenolic-steel, Kevlar/phenolic-titanium, dry fiberglass fabric/aluminum liner, and Kevlar fabric/aluminum liner. All of the rings were evaluated at the Naval Air Warfare Center's (NAWC) rotor spin facility, using the second stage power turbine rotor from the Avco-Lycoming T53 turboshaft engine.

Results have proven that material systems commonly used in lightweight armor applications are more efficient than an equivalent steel system for turbine rotor burst containment, on both a containment ring weight and wall thickness basis, when evaluated using the Avco-Lycoming T-53 second stage power turbine rotor in spin-pit burst experiments at the NAWC. The most efficient system, on a weight basis, was the glass/phenolic composite system and the most efficient system, on a wall thickness basis, was the 6Al-4V titanium system.

Current efforts have been aimed at developing a composite containment system capable of operating at elevated temperatures more closely associated with use in jet engine applications. The system currently being investigated is a fiberglass/silicone composite wrapped onto a nominal one-sixteenth inch aluminum liner. The system has been tested successfully at ambient temperatures. Results from testing at elevated temperatures are currently underway, and are expected to be successful.

ELECTRO-OPTICAL MATERIALS

Crystal Growth of Laser Materials

In the early 1970s gas dynamic lasers were being evaluated for a variety of military applications. A critical element in these lasers was the optical window which had to be transparent and resistant to microplastic deformation at the high temperatures and pressures at which these lasers operate. Sapphire crystals grown by the technique developed at Watertown

for transparent armor, was thought to be an excellent window candidate for carbon monoxide lasers which operated at approximately three microns wavelength. Sapphire has excellent optical transmission at three microns. Researchers at Watertown refined the crystal growing technique and produced several prototype windows, approximately six inches in diameter. However, the Army decided to focus its gas laser work on the carbon dioxide laser which lases at 10.6 microns, where sapphire is opaque. Accordingly, research on sapphire for laser windows was terminated. However, the experience of working with the laser community provided the background and knowledge for future work at Watertown on the growth of solid state laser materials.

The Army's need for lower cost Nd-doped Yttrium Aluminum Garnet (YAG) rods for laser range finders provided the motivation for a program aimed at the improved crystal growth of this material. The Watertown gradient furnace crystal growth technique provided a method that could overcome two major problems in Nd-YAG crystal growth, faceting and coring. These two problems led to over 50% of a crystal grown by the prevailing commercial technology being unusable for laser rods. Scientists at Watertown modified the crystal growth equipment previously used to grow sapphire to grow unfaceted, uncored Nd-YAG (U.S. patents 4,186,046 and 4,510,609). It turned out that while the Watertown crystal growth technique eliminated coring and faceting, and did thereby produce Nd-YAG uniquely suited to several specialized applications, doping levels required for the rangefinder application could not be attained, and the work was terminated.

While the fruits of Watertown's research in crystal growth were never implemented in an Army system, they proved successful in the commercial sector. The basic patent on Watertown's crystal growth technology (U.S. 3,661,676) was licensed by Crystal Systems, Inc., Salem, MA. They have utilized this method for the commercial production of sapphire for optical and electronic application for over twenty years (see Single Crystal Sapphire). In addition, they have adapted the technique to the growth of large polycrystalline silicon for solar energy applications. The ongoing commercial utilization of Army-developed technology by Crystal Systems provides an outstanding example of successful technology transfer.

ALON

ALON, is a new material first produced at Watertown in the late 1970s (U.S. patent 4,241,000). The material is a polycrystalline, nitrogen stabilized cubic aluminum oxide alloy. It has a unique combination of optical and mechanical properties which make it well suited to infra-red or multi-mode missile guidance domes and windows, transparent armor and a variety of other uses. The development of ALON provides an interesting case

history in the serendipity inherent in research and in successful technology transfer.

In the mid 1970s AMMRC was heavily involved in research on silicon nitride for gas turbine application. The key to improving silicon nitride was to have a fundamental understanding of the Si-Al-Y-O-N glass and crystalline phases that exist in the silicon nitride grain boundaries. Thus, a study of the phase relationships in the Si-Al-Y-O-N system was undertaken. As a first step in this project the researchers were investigating the AlN- Al₂O₃ phase diagram. In the process of doing this they discovered that they could make a material that was essentially 100% nitrogen stabilized cubic aluminum oxide. While this phase had been reported in the literature, no one had previously made it as a material and evaluated its properties. When it became evident what a high potential ALON offered, the direction of the initial research program was changed to focus on understanding this new material and optimizing its processing. In the early 1980s a large number of papers were published by Watertown scientists in the scientific literature on the crystal structure, synthesis and properties of ALON.

The opportunities presented by Watertown's development of this new material for infra-red missile guidance applications were brought to the attention of researchers at Raytheon Corp. For several years in the early 1980s Watertown and Raytheon worked collaboratively to evaluate ALON. Subsequently, Raytheon developed its own proprietary processing technology to manufacture ALON materials and components. Raytheon has commercialized this technology, and ALON guidance domes have now been qualified for at least one Army missile system.

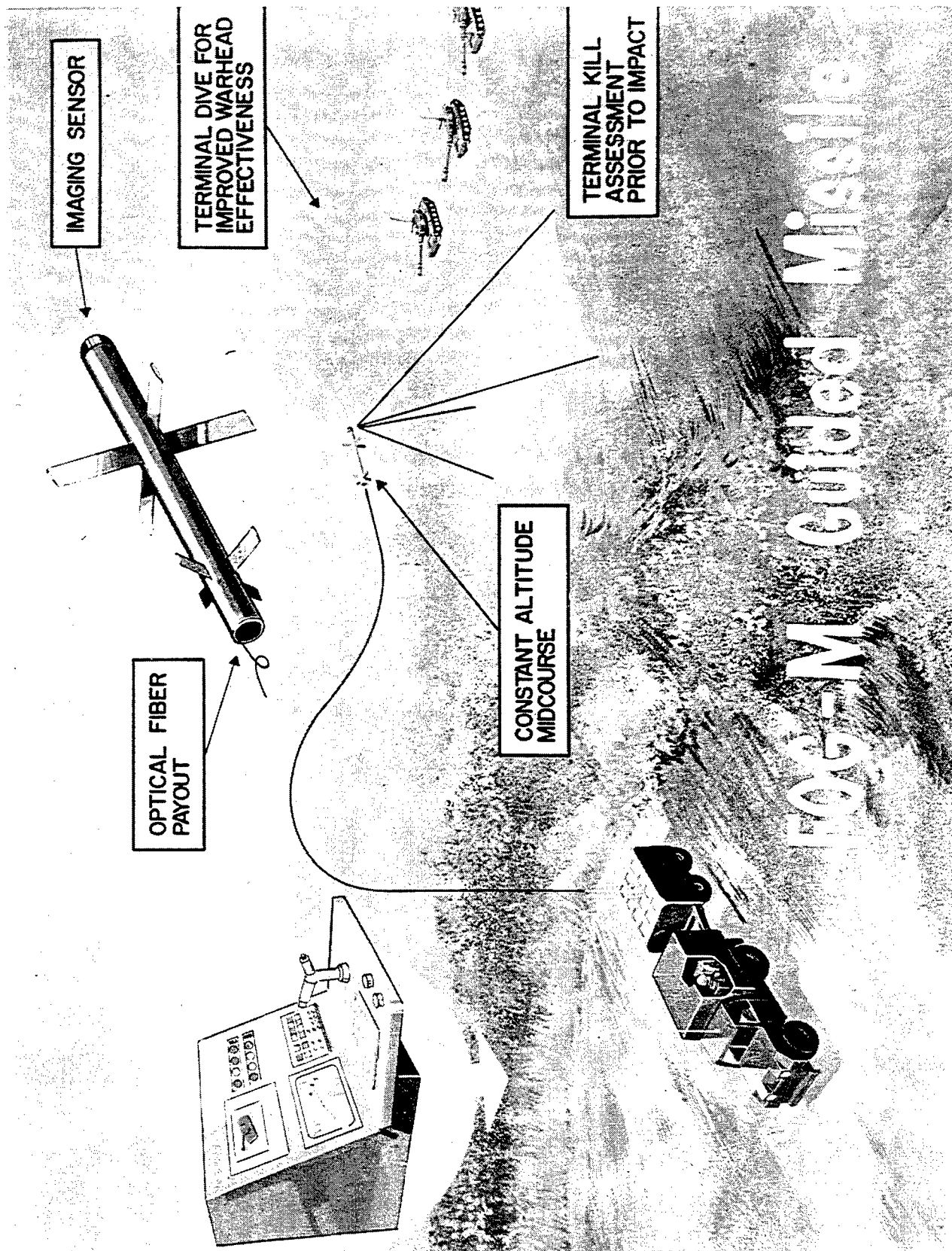
Hermetically Sealed Optical Fibers

At the beginning of the 1980s, the Missile Command of the Army began the research and development of the Fiber Optic Guided Missile (FOG-M).

This is a moderate speed missile of a 10 kilometer range with a television camera and other sensors in the nose. The signals picked up by the sensor package are transmitted on an optical fiber, much the way that optical fibers are being used in ground communication. The optical fiber carries light, which is modulated by the TV and sensor systems. Thus a very large amount of information can be sent back by the missile and a great deal of guidance and control information can be sent from the ground back to the missile on the optical fiber. This missile was tested in concept very successfully.

The problem which attracted much attention and which Watertown addressed and solved was the strength of the optic fiber linking the controller to the missile.

Glass optical fibers, as drawn from the melt are very



Watertown developed coatings for the optical fibers to prevent deterioration in storage.

strong. In common with all ceramics, they have surface flaws. Silicate glasses when formed and exposed to a normal atmosphere are covered immediately with a monolayer of water vapor even under low humidity conditions. The water vapor attacks the silica structure of the glass slowly. When the glass fibers are placed under tension, as they are when they are stored on a spool (bending the glass fiber around the spool places the outer surface of the fiber into tension), microcracks open at the site of the flaws. The inner surfaces of the microcracks are swiftly attacked by water vapor.

As time passes the microcracks, under continuous attack by the water vapor, grow, and the strength of the fiber drops. Over a period of ten years, a typical storage time for Army equipment, the strength drops by orders of magnitude.

In normal practice, glass fibers are not used as drawn; they are coated with polymers to protect them during handling. The normal polymer coatings are not impervious to water vapor; this is not an issue for normal communications systems because the fibers are tied in bundles and wrapped with steel cables which carry the mechanical loads. In the FOG-M, however, the fiber is spun out of the rear of the missile and must carry all of the mechanical and aerodynamic loads of the playout process. The strength of the fibers has to be kept close to its as-drawn value in order to have the missile guided successfully.

An R&D program was set up to evaluate fibers drawn under various conditions, to develop thin coatings for glass fibers which would be impervious to water vapor, and to test all of the commonly manufactured optical fibers, coated and uncoated, under conditions of standard tensile loads and standard humidity conditions at low and high temperatures. Over a period of three years, several coatings were developed which protected the fibers from water vapor attack as determined by long exposures to high temperatures, loads and humidities. The coated fibers retained their strength.

Watertown worked very closely with the fiber manufacturing industry and did a large amount of testing of all fibers provided by many manufacturers and coatings developers and served as an "honest broker" to compare the properties of the various fibers.

The best of the coatings developed were provided to the Missile Command and adopted by industry for use in the FOG-M development program.

Ferroelectric Phase Shifters

Introduction

Phased array antennas can steer transmitted or received signals either linearly or in two dimensions without mechanically oscillating the antenna. These antennas are currently

constructed using ferrite phase shifting elements. Due to the type of circuit requirements necessary to operate these antennas, they are costly, large and heavy. Therefore, the use of these antennas has been limited primarily to military applications which are strategically dependent on such capabilities. In order to make these devices available for many other commercial and military uses, the basic concept of the antenna must be improved. If ferroelectric materials could be used for the phase shifting element instead of ferrites, phased array antennas would be totally revolutionized. The cost of the elements will be reduced from approximately \$5000 to \$200.

History

Fort Monmouth and Watertown began a joint project to develop ferroelectric phase shifters in 1991. A prototype ceramic Barium Strontium Titanite, $\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$ (BSTO), phase shifter using a planar microstrip construction was demonstrated in 1991. However, in order to meet the required performance specifications, maximum phase shifting ability with minimal insertion loss, the materials had to be optimized. As part of this optimization process, various composites of BSTO and non-ferroelectric oxides have been formulated. These formulations have become break-through materials and have electronic properties which had never been previously attained. These are designated as BSTO-Oxide III materials. In 1992-1993 a 10 GHz-4 element phase shifter was demonstrated using bulk ceramic materials at a thickness of three mils. The array had 360 degrees of phase shift with only four dB of loss. From 1993-1994, Harris Corp. demonstrated a 10 GHz ceramic antenna which showed a significant phase shift, and current designs will utilize a large aperture which will reduce the beam width. At this time, 1994-1995, thick film co-planar phase shifters are being fabricated for use at 15 GHz-25 GHz and will be incorporated into a geodesic cone antenna eight element array. Also NRL is incorporating our materials into a traveling wave antenna, and initial tests have also indicated very low loss materials which will be scaled up to two sections by 1996. Thin film fabrication using pulsed laser deposition of Watertown ceramic composite formulations has produced a co-planar phase shifter (35 GHz) which has shown significant phase shift with a low insertion loss. Currently (1995), a Cooperative Research and Development Agreement has been established with Virginia Polytechnic Institute (VPI) to develop Metal Oxide Chemical Vapor Deposition (MOCVD) of thin films, which will provide an efficient means of large film deposition. A TPA has been signed for FY95-FY96 with the Communications and Electronics Command (CECOM) and a Science and Technology Objective has been approved for FY 1996. Additionally, over 25 papers have been published,

and three invited papers have been presented. Two patents have been awarded with another seven currently undergoing the patent process. Technology transfer is being accomplished by patent licensing which is currently underway with several antenna and material processing companies. In conclusion, it is apparent that in the span of four years a major technological barrier has been overcome by Watertown's innovative ceramic formulations and materials processing.

Signature Reduction

Investigations on the microwave properties of materials were begun in the early 1970s as an adjunct to the laser hardening program. It became apparent that monocoque types of composite construction, specifically tail boom structures, which had proven to be extremely tolerant of mechanical and ballistic damage offered many possibilities for incorporation of high energy laser damage tolerant materials in the design of the composite structure. In calculating the effects of novel materials on the mechanical properties of the structural designs, it was realized that other interesting attributes such as the radar signature of the overall structure could be addressed.

As a part of an overall multifunctional design approach for aircraft type structures, signature reduction in the microwave region was explicitly included. A 23mm cannon system had been used in the ballistic testing of the composite structures, so the corresponding radar tracking systems were used to define the explicit frequency bands of interest. A set of circuit analog designs of varying complexity was developed. The most interesting result of the program was the fact that the components used in these types of designs, such as fiberglass-epoxy composite sheets, kapton films, graphite-epoxy sheets, Nomex honeycomb and polyimide foams were very absorptive of high energy laser radiation. The structures therefore survived laser radiation much better than the baseline aircraft construction. The circuit analog designs developed, however, were not tolerant of the thickness variations inherent in the low cost fabrication techniques required for the program, although they could have been produced at costs competitive with those reasonable for high performance aircraft.

Efforts on signature reduction materials resumed in earnest early in FY 86. A multidisciplinary program was established, involving personnel from Watertown and Northeastern University. An important element was the inclusion of personnel who had been involved in the development of the Composite Infantry Fighting Vehicle. This provided a new armor focus for MTL research efforts.

From 1985 to 1992, MTL chaired a series of meetings of an Army Low Observable Materials Steering Group, which was composed of representatives of Army laboratories and ARDEC. The objective

of these meetings was to offer a forum for classified discussion of Army specific problems and possible solutions. One point that became very evident in these meetings was that the Army's needs for low observable materials are very different from those of the Air Force and Navy. This is true both for the range of frequencies that have to be covered, and for the performance demands for the materials for durability in the battlefield.

Major research efforts during this period focused on four major items: 1) understanding the details of the threat environment for ground vehicles; 2) establishing a test laboratory; 3) demonstration of a radar absorbing transparent plastic structure; and 4) development of a series of designs for radar absorbing structural armor, based on graded dielectric and Jaumann absorbers. Most of these required tolerances on physical dimensions and dielectric properties which proved very impractical, and did not in general cover both the microwave and millimeter wave frequencies of concern. However, these efforts did pave the way for the development of alternative approaches which did not suffer these limitations.

Other research efforts included development of an introductory tutorial short course, compilation of a database of information on materials (mostly foreign), and an analysis of environmental effects on rotorcraft radar absorbing secondary structures.

In 1988, Watertown was invited to participate in a group of experts who reviewed the Soviet open literature as applied to low observable materials. This effort was conducted at Science Applications International Corporation, McLean, VA. Watertown's representative contributed chapters to the resulting publication.

Two new materials technologies became available during the late 1980s and early 1990s that enabled development of manufacturable, damage tolerant, radar absorbing materials which are suitable for application to armor systems. These materials could be used either as an applique or as radar absorbing, load bearing, structural armor. The first of these technologies, the development of conductive polymer coated fabrics, proved ideal for fabricating dielectric absorbers. These absorber designs facilitate their manufacture, and allow standard low cost polymer matrix processing technology to be employed.

The second important technology is known as binary optics, which fostered the development of novel textured surfaces for anti-reflective coatings. In bistatic specular reflectance tests off normal incidence, absorbers made with these textured surfaces performed very well. Such surfaces were also found to have a low level of diffuse backscatter.

Samples of a very high performance absorber based on these technologies were fabricated in sufficient quantity for a test which demonstrated clearly their effectiveness on a ground vehicle. Further development of this approach will be continued.

HARDENED BALLISTIC MISSILE DEFENSE MATERIALS DEVELOPMENT

Background

What is now the U.S. Army Research Laboratory-Materials Directorate Ballistic Missile Defense (BMD) Materials Development Program was begun in September 1968 as the U.S. Army Materials and Mechanics Research Center Hardened Materials Development Program. Through March 1983 the threat to which the program responded was advanced maneuvering re-entry systems. During this time period all strategic missile systems carried nuclear warheads such that "Hardened" generally referred to the capability to resist 1) the nuclear environment and 2) the natural environment, i.e., rain, ice, snow, and fine particle dust. The Watertown program chose to limit its technology development program to four areas: 1) Thermal Protection Systems, i.e., nosetips and heatshields; 2) Substructures, i.e., the interceptor principal load carrying component; 3) Propulsion System Components, i.e., rocket nozzles and motor cases but not propellants; and 4) Interceptor Seeker Components, both RF and IR. Because of the specialized or very sophisticated fabrication/manufacturing requirements of these missile system components, it was decided that the principal contributions to the effort by Government Laboratories would be in the area of characterization of the materials and structures which comprised these subsystems. Additionally, a high leveraging of the re-entry vehicle (RV)/interceptor industrial base in these areas could be achieved. Watertown developed the capability to characterize materials prior to and after their inclusion in underground nuclear tests. This capability could not be found elsewhere at any one facility. Interferometer techniques were later developed and added which can evaluate the "shock wave" response of composite substructures, i.e., for a single event the response of the fibers and the resin and the composite can be determined by this technique.

Thermal Protection Systems

During the period 1971 through 1976 the Watertown program developed an all weather nosetip consisting of a carbon/carbon ablator and a tungsten subtip. The nosetip met all requirements for making intercepts deep in the atmosphere but was expensive. With the reduced requirements for SDI/BMDO, Watertown was able to automate ablator weaving and reduce the cost from \$45k/ablator to \$4k for each complete nosetip system.

At the request of both the Ballistic Missile Defense Systems Command and Advanced Technology Center (BMDSC and BMDATC) Watertown conducted the most comprehensive study of "heatshields"

ever performed from 1978 through 1986. The study showed that Tape Wound Quartz and Carbon phenolic heatshields will meet any projected interceptor requirement. From 1986 to 1991 the program developed a low cost, sprayable, heatshield for exo-atmospheric interceptors.

Structures

Prior to 1975 for interceptors, and presently for re-entry systems, substructures have for the most part ended up as aluminum even though other metals such as beryllium, or steel, or nickel based super alloys were initially proposed. Through 1973 the Watertown structures program evaluated 2014-T6, 2024-T6, and 6061-T6 aluminum, CIP/HIP beryllium, and MAR-M200 (a nickel based super alloy), as candidate substructure materials. Using MAR-M200 and precision investment casting, the Watertown program showed that it was possible to fabricate a complete, complex interceptor structure or "metal radome" in one step.

The maneuvering threat soon made it obvious, however, that to meet this threat metal substructures, except for certain missions, would be prohibitively heavy. Even though metals would not meet the requirement without the development of a new massive propulsion system, the state-of-the-art of both resin and metal matrix composites was such that composites were only rarely thought of as serious substructure candidates by strategic missile system prime contractors. In 1974 the Watertown Hardened Materials Development Program began a composite substructure development program, choosing GY70/934 as the resin matrix composite system and boron/aluminum as the metal matrix composite system to be evaluated. Performance and environment survival requirements for the Ballistic Missile Defense Advanced Terminal Interceptor (ATI) were used as Watertown's development goals. The ATI's guidance and control section was chosen as the critical missile section to be evaluated.

For the metal and resin matrix composite substructure development efforts a four phase development program was followed. The first three phases were conducted in subscale: 1) Fabrication of conical sections; 2) Joining of conical sections to adjacent sections; and 3) Attachment of internal components to the composite shell. Fabrication and a full-scale ground test of a composite structure occurred in the final phase.

In the 1983-84 time frame full-scale ground tests of the resin and metal matrix composite ATI Guidance and Control sections were conducted and showed that for both types of composites, resin and metal matrix, all of the goals were met and surpassed. The tests also showed that these composites would show improved performance and be lighter than the system proposed-metal substructures. Throughout this development effort the problem of cost, while necessarily of concern, was specifically not addressed until mission enabling solutions

became available.

The onset of the Strategic Defense Initiative (SDI) program in 1983 ultimately imposed two constraints on the Watertown Materials Development program: cost and improved performance. The constraints were imposed in the following manner: No new technology program(s) could be funded unless it could be shown that the proposed end product would first be less costly and secondly provide improved performance and/or weight reduction over the present or system proposed component.

A 1984-1986 study of SDIO ground based endo- and exo-atmospheric interceptor requirements showed that all of the materials and structures technologies developed for nuclear warhead carrying interceptors were transferable to SDIO interceptors; however, for SDIO the primary emphasis shifted from endo- to exo-atmospheric intercept. The composites technologies were therefore applied to the Exo-atmospheric Re-entry Vehicle Intercept System (ERIS). The ERIS program was "congressionally" constrained to build this new interceptor system using "off-the-shelf" materials, and this resulted in a system with a KV structural weight of 28 lbs. With the full consent of the ERIS project manager and prime contractor (Lockheed Missile Systems Company), the Watertown program used advanced materials to fabricate a resin matrix composite structure weighing 12.2 lbs. with a 40% increase in stiffness, and a boron-aluminum/silicon carbide-aluminum metal matrix composite weighing 15 lbs. with a 22% increase in stiffness. These improvements were so impressive that the ERIS project manager agreed to evaluate the resin matrix composite by flying this new structure on the fourth ERIS Demonstration/ Validation flight test. Unfortunately, however, Congressional re-direction of the SDIO program prevented this flight test.

The system which replaced the ERIS was the Ground Based Interceptor (GBI) system. Physically it was smaller than ERIS; the structure being 20 inches long as opposed to the 55 inch long ERIS structure. The GBI structural weight goal was 6 lbs., and the structural stiffness requirement was over seven times that of ERIS.

At this point in its composite structures development program, Watertown departed from the traditional three layer missile structure consisting of a totally insulating thermal protection layer (heatshield) bonded to a load carrying substructure. Because the heatshield was required to keep the substructure cool, the thermal protection layer frequently weighed up to 30% of the Kill Vehicle structural weight. Since the temperature rise in an interceptor structure is for such a short time, one way to reduce weight was to allow the temperature in the substructure to rise by reducing the thickness of the thermal protection layer. Because interceptor heatshields were tape wound ablators and these ablator tapes were not made in many small widths, thereby requiring extensive heatshield machining to achieve "thin heatshields," this method of weight reduction was not cost effective. The program has evaluated a series of resins

which will allow the structure temperature to rise to as high as 1200°F for a few seconds. At present the program has settled on a resin system which can operate in the 600-700°F range, and which also shows the least water absorption and outgassing tendencies.

During this same time period (approximately 1988-1992) the major advance in the composite structures development effort came through the development of a process called Matched Metal Net Molding (MMNM). This is a closed mold fabrication process which allows fabrication of the composite missile substructure in one step. This process has allowed development of strategic interceptor structures with weight reductions of 30 to 50%, increased stiffness, and projected production cost reductions of generally 50%. The process has been applied with equal success to both the primary load carrying structure and internal components. The flexibility of the process is such that it has allowed development of structures which perform more than one function, i.e., in addition to being load carrying structures, the substructure can serve as the electrical ground plane; can have passive damping layers added; and can provide environmental protection as needed or required. The MMNM process allows fabrication of multi-functional substructures.

Through the use of this new closed mold fabrication process, the Watertown program fabricated a generic GBI structure weighing 6.5 lbs. with a structural stiffness exceeding its 300 Hz. goal. At the request of one of the GBI competing contractors, the program fabricated a GBI candidate structure whose structural stiffness exceeded 400 Hz. and weighed about the same as the generic structure.

It has long been the desire of strategic missile system program managers to include as one of the systems development requirements long term storage with a minimum of environmental control. Through 1990 this factor alone was sufficient to keep a healthy and rigorous metal matrix composite structures program on-going despite the obvious immaturity of continuous fiber reinforced metal matrix composite systems other than boron aluminum.

The Watertown reward for belief in the capability of MMCs came with the selection of B/Al as the projectile material for the BMDO electromagnetic (EM) gun program. With the highest compressive strength available B/Al was the only material from which the EM gun projectile could be fabricated. The Watertown program successfully developed and demonstrated a new approach for small diameter thick walled frusta.

Optical Seeker Component Development

From the inception of the program in 1968 through 1986, the optical seeker component development program had two principal tasks: 1) the development of a nuclear hardened primary mirror

for the Long Wave Infrared (LWIR) optical seeker used by exo-atmospheric interceptors (Re-entry systems in mid-course radiate at LWIR frequencies); and 2) the development of RF/IR Antenna Window/Dome materials for endo-atmospheric terminal intercepts.

Hardened LWIR Primary Mirror and Baffle Development

Because the primary mirror of an exo-atmospheric interceptor had to be hardened against a nuclear environment, and to operate at cryogenic temperatures (4°K) "above ground," believable, simulation techniques (techniques which simulated the anticipated nuclear and "optical" environments to be encountered) had to be developed to evaluate candidate systems at these temperatures. The ability to produce hardened beryllium mirrors which met the optical performance requirements was ultimately demonstrated by a large Government/University/Industry joint working group which included the Watertown program.

In 1987 Watertown re-established its program to develop nuclear hardened optical baffles. In general an optical seeker baffle is a cylinder with internal "vanes." Both the internal surface of the cylinder and the vanes have been made opaque over a range of frequencies whose purpose is to keep stray electromagnetic radiation from getting to the detection system. Over the 1968-1976 period Watertown did have an on-going baffle materials development program, but this was stopped as much because there was no clearly successful path to develop a hardened baffle, as it was stopped to concentrate on the more critical mirror effort at that time. In 1986 a Watertown scientist proposed the use of ion beam deposition on aluminum and beryllium as a solution to the dilemma. A very successful program followed, and in 1990 the Watertown program fabricated six full-scale optical baffles. Two of these full-scale aluminum baffles were flown on the Clementine satellite which successfully mapped the surface of the moon.

RF/IR Antenna Window/Dome Materials Development

Over the period from 1968 through 1985 the development of antenna window/dome materials and structures was a principal task in the Watertown strategic missile system composite structures development program. The majority of the effort was centered around the development/improvement of multi-dimensionally woven (i.e., 3D and 4D) fiber reinforced preforms and high purity matrix materials. From 1969 through 1973, program goals were driven by the performance and environment survival requirements necessary for advanced BMD interceptor antenna windows. Initial emphasis was placed on achieving an order of magnitude improvement in hardening against nuclear effects and dust/

particle impacts.

The multi-dimensionally woven (4D) high purity quartz fiber/silicone resin composite developed proved to be an extremely "hard" antenna window. It established the basis for a one to two order of magnitude fracture toughness improvement. From 1973 to 1978, using the 4D weave, densified with an inorganic high purity silica resin, the program produced a composite antenna window having no RF heat flux related transmission problems, and having the highest nuclear hardened spall threshold of any window tested up to that time.

Because of the predicted large number of "incoming re-entry vehicles" and the projected large size of the U.S. interceptor radomes, the question of availability of high purity quartz fiber became a problem and was solved when Watertown sponsored the development of a U.S. capability to manufacture high purity quartz fiber beginning in 1986. Up to that time most high purity quartz fiber came from France. The development of this U.S. domestic source of high purity quartz fiber was highly successful.

Comparison of the U.S. produced and French produced quartz fibers was accomplished through fabrication of two full size radomes having constant fiber volume, using the Navy-sponsored automated-weaving capability at FMI, Biddeford, ME. The preforms were successfully densified by GE-RESD (the General Electric Company's Re-Entry Systems Division). A further manufacturing improvement occurred with the development by GE of its now patented "4D Triangular Reinforcement Design."

With the improvements in weaving techniques and in resin chemistry, the USARL-MD radome materials program has proposed the development of a "one electrical wall thickness" radome, having 30-40% weight reduction and a projected 50% cost reduction to the PAC-3 Program.

The MAR M-200 precision casting technology developed for interceptor structures was also adapted to demonstrate the fabrication feasibility and thermostructural survivability of a heatsink "metal radome" whose millimeter wave electrical design had been developed for BMDO interceptors.

Propulsion System Components

In 1987 the Watertown program began the effort to determine the feasibility of using automated weaving techniques to fabricate a one piece solid rocket motor nozzle system for both endo- and exo-atmospheric interceptors. The effort quickly showed that a one piece multi-dimensionally woven (i.e., 3-D) nozzle system was possible. It was also quickly shown that this proposed 3-D nozzle system would be an "overkill" for projected BMDO interceptors. The program settled on a two phase approach, evaluating first a two piece nozzle consisting of a multi-dimensionally woven ITE (Integral Throat Entrance) joined to a

braided Exit Cone. This nozzle was termed "revolutionary" by the GBI (Ground Based Interceptor) project manager because it weighed 25% less, maintained high pressure longer, and cost less than the proposed system concept. The second phase of the task was supposed to develop an all-braid one-piece system. Before this could begin, however, the GBI project manager requested that it be determined if the highly successful two piece system could be converted from a static (non-movable) nozzle system to a vectorable nozzle system. This task is presently on-going and has shown the feasibility of the "movable" nozzle assembly. A full-scale static firing will take place during 4QFY95. Of major significance to the advancement of the ARL thermal protection system concept development efforts was the introduction of braiding into the program.

Hardened Materials Development Program-Direction

Based on the success achieved with the development of the technologies described above the Watertown Hardened Materials Development program has initiated a program whose objective is to significantly reduce interceptor weight and volume through the integration of the functions of thermal protection, structures and power consistent with the philosophy of advanced interceptor design. The two critical requirements for BMDO interceptors are cost and weight reduction. The planned program, as described below, is a very ambitious effort, but one based on the technologies which have been, and continue to be, demonstrated by a successful Government Laboratory/Contractor team.

Using this combined Government Laboratory/Contractor team, Watertown has been quickly able to help solve TMD interceptor internal component cost and weight problems, while at the same time achieving increased/improved performance. For the PAC-2 interceptor, working in conjunction with the system prime contractor, RAYTHEON, the ARL team is in the process of replacing three internal metal components with two lighter weight, lower cost resin matrix composites which will have improved performance. The aluminum H-frame battery holder weighs 4.9 kgs. It can be replaced with a composite which weighs 2.1 kgs., costs approximately 50% less to manufacture, and is multi-functional in performance. The two piece aluminum bulkhead and antenna pedestal weighs 2.6 kgs. and can be replaced with a one piece combined composite weighing 1.5 kgs. which is estimated to cost 40% less and which will be multi-functional in performance capability. The Matched Metal Net Molding (MMNM) "one-step" fabrication technique described above is being used to accomplish the cost and weight reductions as well as the performance improvements.

It was noted above that improved optical seeker performance is required, and that the Watertown program has used advanced fibers and resin systems to partially achieve these goals. It

was also noted that advanced composite substructures must be multi-functional in performance capability, i.e., in addition to meeting greatly increased structural performance requirements, these new composite substructures must serve as the electrical ground plane, give increased damping, be capable of the necessary levels of environmental protection, and also be capable of high temperature operation for short periods of time. However, very little is known about these new high stiffness multi-functional composites, especially under high heating rate conditions. Complete characterization of one of these advanced resin matrix composite systems consisting of the M60J fiber and a cyanate ester resin is being accomplished by the USARL Materials Directorate.

A second critical area being evaluated by USARL-MD is the potential use of ion beam deposition to reduce subsurface damage to optical seeker windows which occurs during polishing of the windows. Grinding and polishing introduce subsurface damage (SSD) in sapphire. If boule to boule reproduction is established and the window blanks taken from the boules can be processed close to final required thickness then ion beam enhanced deposition can be used to polish the sapphire with minimal SSD introduction. Boule reproduction and window size fabrication improvement are being handled by Crystal Systems Inc.

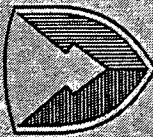
The central task in the Hardened Materials Program composite technology advancement effort to be accomplished under the above noted Government/contractor team, has three principal subtasks: 1) development of a composite shroud; 2) advanced nosetip development; and 3) integrated structure development. The principal contractor is FMI. The contract tasks however, because of the complexity, will be carried out by a team.

The goal of this effort, if totally successful, is 1) to develop a composite shroud system for endo-atmospheric interceptors capable of operating at dynamic pressures in excess of 2.0 MPa; and 2) to determine the feasibility of and the path necessary to transition strategic missile system structures from the traditional three layer structure (i.e., TPS-Bond-Substructure) to a one layer integrated system which performs both the thermal protection and load carrying requirements. This transition will have to take place in two steps. Transition to a two layer structure in which the bond layer is eliminated has already been proposed. The combination of the one step MMNM structures fabrication process and the replacement of the traditional tape wound heat shield with an all braid heat shield now allow ARL to propose/demonstrate replacement of the three layer missile structure with a two layer structure where the bond layer has been removed. Transition from the two layer substructure to a single layer structure will not be quite as easy.

A goal of at least equal importance is advancement of the above noted all-weather nosetip performance capability such that it can successfully operate in the five to fifteen kilometer altitude range at velocities up to six kilometers/sec. The



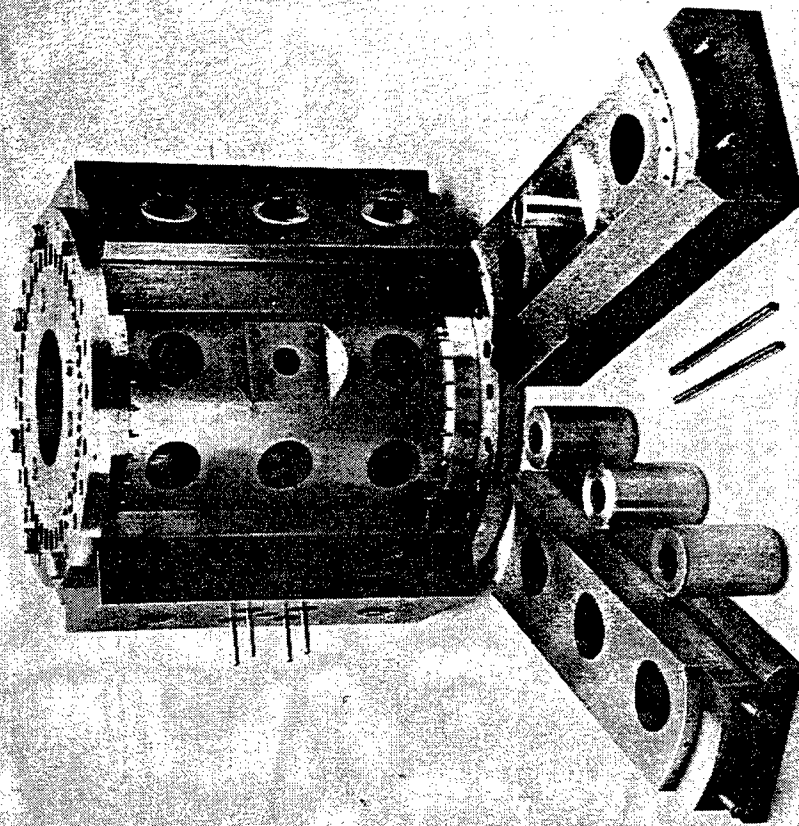
LIGHTWEIGHT STRUCTURAL MATERIALS MANUFACTURING/PROCESSING SCIENCE & TECHNOLOGY



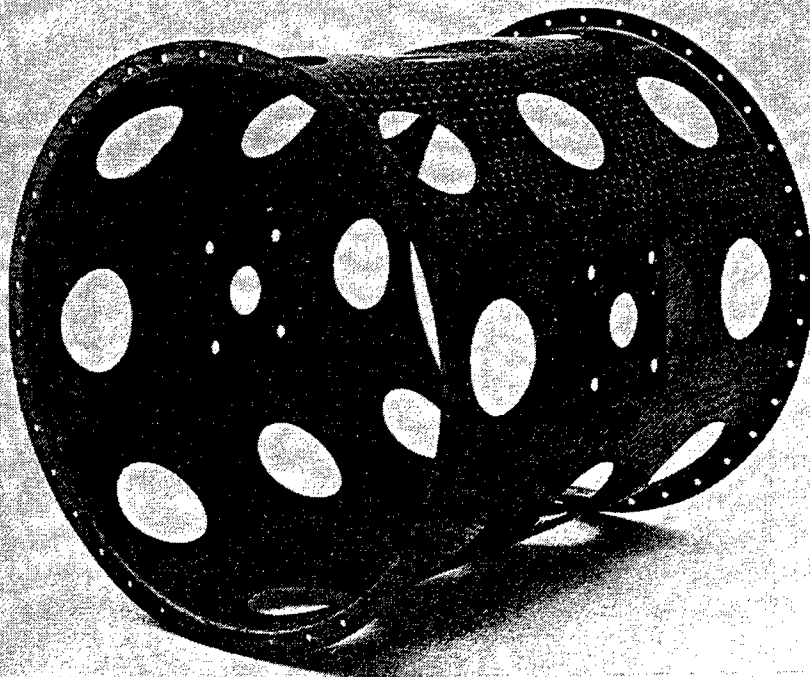
US ARMY
LABORATORY COMMAND

MATERIALS TECHNOLOGY LABORATORY

MATCHED METAL TOOLING FOR NET SHAPE MOLDING OF ADVANCED THERMOSET COMPOSITES



Matched Metal Mold



Graphite Reinforced Bismaleimide
Structural Bridge

complexity and diversity of the technologies necessary to accomplish this overall goal instantly tells why the very sophisticated team which includes the USARL Materials Directorate was assembled.

CHEMICAL DEFENSE

Introduction

Although current polymeric materials are considered to be adequate for field use, the Army continues to investigate novel or advanced materials for military systems that may be exposed to a hostile chemical warfare (CW) environment. Such systems include those specifically intended to protect personnel from CW threats (e.g., protective clothing, gas masks, and emergency shelters), and those polymer-based systems with a service function unrelated to CW (e.g., vehicle tires, track pads, hoses, belts, and gaskets) but required to resist degradation in performance when exposed to CW agents and decontaminants. Watertown's goal has been to design, modify, and utilize materials that will be better agent barriers, lighter weight, more flexible, more fire resistant, less susceptible to chemicals, abrasion, and elevated temperatures, and more resistant to environmental degradation.

Besides material development and adaptation, the objective of this program is to achieve a better understanding of the interactions of CW liquids (agents, simulants, and decontaminants) with various types of materials whose generic properties suggest their use as candidates or model materials in CW-resistant Army systems. Interaction means the solution and transport of liquids in the materials, more precisely described as the sorption, diffusion, and permeation of liquids into and through the materials of interest. This effort is thus materials oriented, dealing with properties, responses, and interactions of materials. This effort does not attempt to deal with the biological or physiological effects of CW agents, and it is involved only very indirectly with the chemistry of agents or the chemistry of decontamination processes. Improved knowledge and quantification of responsive polymers to CW liquids will lead to more realistic evaluation and utilization of the materials in Army systems. Such advancement in knowledge of materials characteristics and materials response comprises the objective of this program and serves as the technology area deliverable. This program responds to Army requirements because the interaction results will provide information about chemical survivability, as mandated by AR 70-71 and DoDD 5000.2.

Scope and Categories of Activity

During the past 15 years, the efforts performed by Watertown regarding Chemical Protection have fallen into two principal areas. They are 1) Materials Development and 2) Interactions of Materials with CW Liquids.

Materials Development has, in turn, encompassed several categories, i.e., Synthesis, Processing and Formulation, and Material Combinations.

In-house synthesis has been devoted mostly to polyurethanes for evaluation as candidates for flexible barriers to CW agents. Studies of processing and formulation have included investigation of production problems with prototype flexible polyurethane lenses and implementation of reaction injection molding (RIM) as a means of producing useful test specimens of polyurethane materials. It also includes formulation and fabrication of a variety of butyl rubbers for evaluation as permeation control materials for CW protective glove qualification tests. Investigation of material combinations has fallen into several areas. These include: 1) blends of rubbers for study of their barrier, mechanical, and stability properties; 2) surface treatments or coatings by plasma deposition, ion implantation, fluorocarbon films, Parylene films, and diamond-like carbon films for investigation of their barrier and durability properties; and 3) laminar composites of unlike rubbers as candidates for good barriers, chemical resistance and wearer comfort.

The other main area has been Interactions of Materials with CW Liquids. This has been concerned mostly with Transport Behavior, and to a much lesser extent with Material Degradation.

Transport behavior refers to the sorption, diffusion and permeation of small molecules into and through the material. This work can be described in three groups as 1) applied studies; 2) test methodology; and 3) fundamental studies.

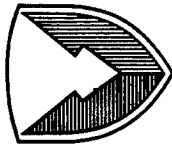
Applied studies have involved: in-house experiments of material sorption of solvents and CW simulants from the vapor state and the liquid state; in-house material permeation experiments by flooded liquid and droplet challenges; contractor droplet permeation tests of materials by CW agents and simulants; and in-house correlation of many of these results with the properties of the barrier material and the penetrant.

In-house test methodology efforts include: adaptation of the MIL-STD-282 Method 204 permeation test to employ a simulant in place of the agent; successful deployment of the Radian permeation cell with the Minicams detector and analyzer; and preliminary trials of a GC/MS instrument for detection of permeant molecules.

Fundamental studies include: the in-house development of a mathematical model of liquid droplet permeation through materials to describe the transient interactions; a review of recent developments in the fundamental understanding of gas permeation through rubbers; and adaptation of a molecular dynamics modeling

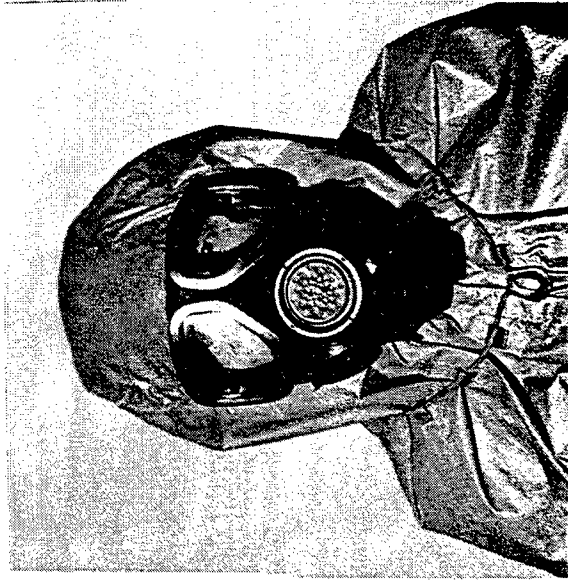


IMPROVED CHEMICAL PROTECTION MATERIALS FOR THE SOLDIER

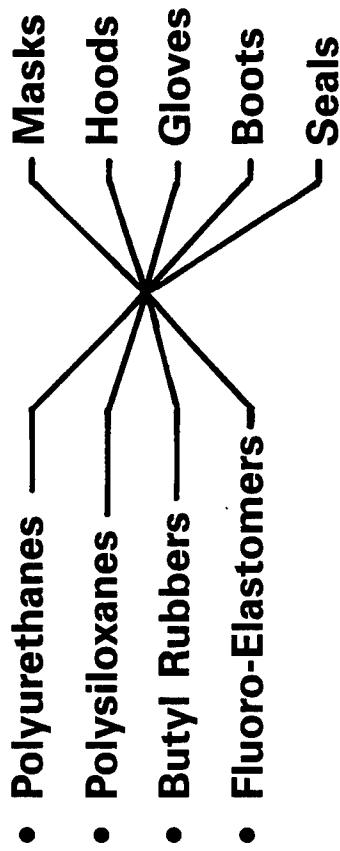


US ARMY
LABORATORY COMMAND

MATERIALS TECHNOLOGY LABORATORY



BARRIER MATERIALS FAMILIES APPLICATIONS



PROGRAM FOCUS

- Screening Advanced Materials
- Develop New Butyl Rubber Blends
- Develop New Polyurethane Compositions
- Evaluate CVD Coatings For Transparent Polymers

program of diffusion in rubbery polymers to permit execution on a massively parallel supercomputer. Also included are experimental determinations of short-chain branching in polyethylenes, and use of synchrotron x-ray diffraction to characterize the morphology of polyurethanes.

Studies of material degradation have involved: 1) the effects of decontaminants upon the mechanical properties of rubbers; and 2) the effects of droplets of CW simulants, fuel simulants, and decontaminants upon coated rubbers and transparent plastics.

Accomplishments

As a way of summarizing and highlighting the activities, results, and potential benefits of this Chemical Protection program, the following list of accomplishments is presented.

- For CRDEC, synthesized, processed, and evaluated selected transparent polyurethanes as possible candidate materials for flexible protective lenses.
- For CRDEC, investigated simulant vapor sorption by rug fibers and wall paint.
- Acquired, characterized, and distributed two sets of "standard rubbers" for chemical defense investigations.
- Attributed anomalous vapor sorption and diffusion in certain polyurethanes to solvent-induced relaxation, thermodynamic swelling, and compositional variations.
- As funded by TACOM, screened the interactions of standard rubbers with CW liquids.
- Prepared several hydrophilic polyurethanes and delivered to NRDEC as candidate matrix materials for Flintstone.
- For TACOM, characterized the formulation, properties, and CW simulant interactions of vehicle track and suspension rubbers.
- As funded by TACOM, sponsored and monitored contractor-performed large-scale systematic agent and simulant droplet permeation tests with the standard rubbers.
- Analyzed and correlated results of contractor-performed droplet permeation tests with the standard rubbers.
- Developed mathematical model for droplet permeation through barrier materials.
- Enhanced the realism of this model by incorporation of mass transfer resistance and concentration dependence of the diffusion coefficient.
- Used vapor sorption tests to show that natural rubber specimens underwent reduced swelling at higher carbon black loadings and exhibited complications in sorption and diffusion processes.
- Employed vapor sorption techniques to reveal the concentration dependence of diffusion coefficients.

- Sponsored investigation of rubber surface modification by fluorine ions and compounds.
- In conjunction with NRDEC, produced and characterized blends of neoprene with other rubbers as possible candidates for protective use.
- Perfected and performed environmental stress cracking tests upon transparent plastics.
- Investigated solvent-induced crystallization of polycarbonate/polyester blends.
- For degradation of polycarbonate by DS-2, identified the most aggressive DS-2 component and the mechanism of chemical attack.
- Developed residual stress model to account for solvent-enhanced crack growth in thermoplastic resin-based composites.
- Formulated and fabricated a number of butyl rubber sheet compounds as candidate permeation control materials for the Product Assurance Directorate.
- Adapted the MIL-STD-282 Method 204 permeation test to operate with simulant CEES.
- For CRDEC, investigated swelling effects of candidate microemulsion decontaminants upon standard rubber materials.
- For CRDEC, determined the effects upon mechanical properties produced in standard rubbers by exposure to three decontaminants; fluorocarbon rubber found to be susceptible to cracking.
- For CRDEC, conducted a survey of facepiece materials and processes; later performed a RESPO 21 materials investigation.
- For RESPO 21 facepiece material candidates, have investigated blends of bromobutyl rubber, have synthesized polyurethanes with polyolefin soft segments, and have studied silicone-modified EPDM rubber materials.
- For RESPO 21 lens candidates, investigated transparent coatings of Parylene C and diamond-like carbon (DLC) upon polycarbonate.
- Employed wide-angle x-ray scattering for precise determination of lattice parameters and short-chain branching in candidate polyethylene resins.
- For NRDEC, characterized the barrier properties of a series of rubber laminates, various butyl rubber compounds, and Parylene N coated rubber materials.
- For NRDEC, investigated the properties and RIM fabrication of unreinforced and reinforced thin films of polyurethane elastomers based on a hydroxy-terminated polyethylene.
- For NRDEC, have sponsored fabrication and distribution of specimens of a candidate commercial polyphosphazene fluoroelastomer for aging, POL, and CW exposure studies.
- Showed that CEES permeation breakthrough times with rubber laminates can be fairly well described with a published two-layer lag time model.

- Synthesized and identified a polyurethane formulation containing 90 weight percent of polyethylene as a candidate for chemical-protective use.
- Characterized and identified two transparent hardcoating materials for polycarbonate as promising candidates for protective lenses.
- Have conducted Minicams permeation experiments with DMSO to show the effects of carbon black loading, polarity index of the rubber and temperature.
- With NRDEC, demonstrated prototype DLC coated sun-wind goggles.
- Published a review of recent developments in the fundamentals of gas permeation in rubbery polymers.
- Employed synchrotron x-ray diffraction to characterize the morphology of in-house synthesized polyurethane elastomers.
- Established the capability for modeling the diffusion in rubbery polymers by means of molecular dynamics treatment.

Weteye Bombs

A test during the spring of 1978 of the stockpile of GB-filled Weteye bombs at Rocky Mountain Arsenal (RMA) in preparation for the bombs' transfer revealed three leaking bombs, leading to the assembling of a Special Surveillance Inspection (SSI) Task Group, in which AMMRC would play a prominent role.

A Navy munition (MK 116, MOD O Chemical Bomb), Weteye is a bomb containing nerve gas. Its production and storage responsibility rested with the Army. Filled in 1969, the Weteye bombs had been stored in igloos at Rocky Mountain Arsenal in steel shipping containers, awaiting demilitarization. Located in suburban Denver, the arsenal is virtually at the end of a runway at Stapleton Airport. For a number of reasons the Army and Colorado congressional delegation were uncomfortable with having a large number of nerve gas weapons installed close to a large population center, especially one with much petrochemical industry. When the DoD suspended planning for demilitarization of the stored Weteye bombs in 1976, plans were made to move them to Tooele Army Depot in Utah for retention as part of the chemical weapon deterrent stockpile.

Prior to the proposed move, the annual surveillance leak testing of the Weteye bombs was conducted in March 1978, with the procedure having been extended to test 100% of the stockpile rather than the usual random sample. One hermetically sealed shipping container was found to contain GB agent vapor. When the first phase of the movement of the bombs to Tooele was conducted at RMA in June 1978, a process which included leak testing, inspection of the bombs and pressure testing of the sealed shipping containers, two more bombs were discovered to be leaking.

Although all the leakage was contained by the steel shipping containers with no vapor escaping into the atmosphere, a Special Surveillance Inspection team was quickly assembled. The SSI group, including team members from RMA, AMMRC, other components of the Army, universities and private contractors, was tasked with determining how bad the leaks were, whether the leaking bombs could be safely transported and why they were leaking. Were there only a few bad ones, the result of manufacturing defects, with the majority being good? Could those about to leak be detected by NDT? The Colorado State Department of Health was represented through its invited observers.

The Weteyes were moved to a disassembly plant where the bomb components were drilled and agent samples collected and sent to RMA and the Colorado School of Mines for chemical analyses. After performing analysis of GB agent samples from both leaking and non-leaking Weteye bombs, researchers determined that the agent was of high purity with adequate concentrations of inhibitors to continue in storage indefinitely. The chemical analysis data presented no evidence of corrosion of the bomb bodies by the agent.

Additional testing involved the cutting of metallurgical samples which were then forwarded to AMMRC for metallurgical evaluation. At AMMRC, initial testing consisted of extensive visual observation, photography, NDT and X-Ray radiography. The leaks on all three bombs occurred at the filler boss weld at approximately the 12 o'clock position above the fill port. Dissecting cuts allowed further metallurgical and chemical analysis. Observation of the corroded welds provided evidence that the eutectic structure in the weld interdendritic regions is a preferred path for corrosion. Team members believed that crevice corrosion was the reason for the corrosive attack beginning at the root of the weld. Because of the design of the sealing and the level at which the liquid was sealed, a corrosive process was initiated in which the chemical composition of the stagnant liquid became different than that of the main body of the liquid, resulting in metal corrosion in the crevice area. When the corrosive channel penetrated through the weld to the outside atmosphere, corrosion was accelerated due to hydrolysis decomposition of the agent GB which produced hydrofluoric acid. It appeared that the welds most susceptible to corrosion would be those having large, continuous interdendritic boundaries leading straight toward the outside surface of the weld from the root of the weld. Corrosion would be further facilitated by residual tensile stresses normal to the region, weld tears, weld voids and higher than normal porosity.

At the conclusion of testing, the SSI team was able to state that they had found no indication that the safety of the proposed movement to Tooele would be affected by any corrosion failure of the bomb bodies. Decomposition was not likely in the foreseeable future; despite the probability of additional leakers in future years it was unlikely that individual bombs would fail catastrophically or that the stockpile would suddenly become

unserviceable.

The need for a SSI had resulted in the movement of the Weteye bombs to Tooele Army Depot being rescheduled to begin June 11, 1979. A second 100% leak test conducted from May 21 to June 4, 1979 disclosed six shipping containers with GB vapor levels in excess of 0.0001 mg/m³. The number of defective bombs partly reflected the acceptance of a new criterion level harsher by a factor of 10 than that used in the 1978 pre-movement leak testing. Movement again was postponed in order to conduct a reassessment inspection along the lines of the 1978 inspection.

Findings of the Weteye Reassessment Inspection indicated that the bombs were suitable for continued storage, and that the safety of the movement remained unaffected. The team concluded that because of the slowness of the corrosion process and microscopic nature of the leaks the structural integrity of the bombs remained unimpaired.

Weteye bombs are no longer being produced. The discovery of leaks in 1978 and 1979 pointed out the need to adopt a binary weapon approach should chemical weapons be manufactured in the future. Binary weapons contain no toxic agents. Rather, two non-toxic components are in a shell, the agents separated by a diaphragm or similar barrier. Upon firing the diaphragm breaks, permitting the two parts to mix, thus forming a chemical weapon.

Throughout the Weteye inspection process, the objectives were: to find out what the problem was; to protect community safety during movement and storage; to assess the utility of the Weteye bomb for Navy use; and to allay fears. In both the 1978 and 1979 inspections researchers from AMMRC made available their technical expertise, not only in the testing process, but also by briefing congressional delegations and HEW officials, meeting with concerned local groups in Tooele and being available to give testimony in court. Once again, Watertown personnel were part of a team effort which applied laboratory research to the investigation of a potentially disastrous condition, to obtain an informed assessment and to pave the way for systemic evaluation and design modification.

Chemical Weapons Stockpile Reliability Program

After the successful completion of the activities of the Special Surveillance Inspection Task Groups during 1978 and 1979, which investigated leaking Weteye bombs in storage at Rocky Mountain Arsenal, the entire stockpile of Weteye bombs was successfully moved from Denver, CO to the Tooele Army Depot in Tooele, Utah. Here they could be stored under safer conditions and subsequently demilitarized. Attention then turned to the other chemical weapons in the Army's arsenal, by means of a formal Stockpile Reliability Program. Because of AMMRC's important contribution to the Weteye program, the agency was

again asked to participate, providing its materials expertise, particularly as pertaining to the metal parts.

The changing global scene, in terms of foreign threats, as well as political considerations, both domestic and international, forced a reassessment of the role of chemical weapons. As a result, there would be a transfer of the weapons to a smaller number of installations, where they could be more safely stored, and when no longer needed, eventually efficiently and safely demilitarized.

Again, the questions included such factors as: whether the weapons were still serviceable and effective; could they easily and safely be moved to another site for storage and/or demilitarization; were any weapons leaking; could these leaking weapons be safely moved; as well as such factors as why were they leaking and what could be done to predict leakers and prevent future occurrences of leaking weapons.

A number of chemical weapons were evaluated. After the Weteye bomb, the next weapon system evaluated was the 105-mm GB, M360 projectile in 1981. These were steel artillery projectiles containing liquid agent, with a steel burster tube press fitted into the projectile body. In a few cases agent had leaked from the projectile body into the burster tube and then into the enclosing storage igloo. It was found that both one piece and two piece burster tubes had been used in production, and that all leakers were found to occur in projectiles with two piece burster tubes. In these tubes, end plugs cut from resulfurized free-machining steel rod, were brazed into AISI 1020 steel tubing. Corrosion occurred primarily in the vicinity of the brazed joints, which were found to contain considerable porosity. In addition, corrosion was found in the end cap itself, at the interface between the sulfides and the steel matrix, where the stringered sulfides intersected the surface of the end cap. This study allowed the Army to identify those projectiles with the two piece burster tubes as the most susceptible to corrosion and leaking.

In 1983 the investigation was extended to another weapon, the 155 mm M121/121A1 GB projectile. The design of the 155 mm projectile is similar to that of the 105-mm M360, a steel projectile body which carries the GB agent, and a steel burster tube which is press fitted into the projectile body. Again, two types of burster tubes were used, a one piece design, and a two piece design with an end piece brazed to the cylindrical tube. All leakers were found in those projectiles with a two piece burster tube, with the leaks located at poorly brazed joints, and with associated corrosion at that area. The only difference in this case was that the end plug for the burster tube in the 155 mm M121 projectile was cut from a plain carbon steel plate, rather than the resulfurized free-machining bar stock as in the 105-mm M360. As a result, there was no serious corrosion of the end plug itself in the larger projectile.

A larger effort was next initiated in 1985 on an assessment of deterioration in the M55 rocket system. This system is a 4.5

inch rocket, produced from aluminum alloy 6061-T6. An aluminum burster tube of the same composition is welded inside the rocket body. The entire system was stored in a fiberglass shipping container. There were two manufacturers of the system, with different design of burster tubes and fill ports, different weld alloy, as well as four different types of agent.

Both nonleaking and leaking rockets were investigated. Pitting corrosion was the primary failure mode, found in leaking and non-leaking (i.e., not yet leaking) rockets. The extent of pitting varied markedly with the agent type, in the case of one agent, 64% of the rockets being severely corroded. Although some corrosion was found in the fully immersed burster tubes (presumably near extrusion defects) and in the rocket body, most corrosion pits were at or near the liquid level line in the stored rocket, or in the vicinity of gelled agent where that occurred. In the most extreme cases, extensive leaking of agent occurred, and the structural integrity of the rocket was affected.

The results of the investigation allowed recommendations to be made, including elimination from the stockpile of those rockets with the most corrosive agent, and periodic rotation of the rockets during storage, so that the location of the liquid level is changed.

In addition, a study was made of the M441 shipping containers for the M55 rocket from several depots. These fiberglass containers are used for storage and transport, and in addition to providing mechanical protection to stored rockets, should provide protection from any leakage of agent. Two different designs of container had been produced, although the containers from the depots were all of the older design. In addition, two types of finish were noted, a "dull" finish associated with mat fibers, and a "shiny" finish associated with chopped fibers. Porosity was greater in the mat fiber tubes. Leak tests performed on shipping containers and sections cut from containers showed leakage at the end caps, where O-rings had undergone permanent set. In addition, significant through wall leaks were found on samples with mat fibers, whereas few were found with chopped fiber leakers. Recommendations to prevent the shipping containers from leaking during storage or transportation included various methods of encapsulating the shipping tubes.

The last systems evaluated were MC-1 750-lb bombs and MK-94 Mod O 500-lb bombs. These bombs are produced from a 1% manganese medium carbon steel. For lifting purposes, a strongback is welded into each bomb, which process is followed by heat treatment. Several leaking bombs were investigated, and visual examination supplemented by helium leak testing showed that leaks occurred in the welded area, except for two bombs which had been drilled for agent sampling purposes. When the leaks were associated with the weld in the strongback area, careful metallographic investigation revealed corrosion always associated with a weld crater crack on the outside surface and weld defects, i.e., cracking, porosity, and lack of fusion in the sub-surface

region. These problems were attributed to poor welding practice and quality control. The leaks associated with the drilled and tapped hole revealed very poor fit between the tapped sample hole and the threads of the plug.

The results of the Watertown analyses were very helpful to the overall Stockpile Reliability Program. In most cases (all, except for the M55 rocket), the leaks were associated with welded or brazed areas. Often, poor joining practice could lead to porosity or weld cracking, eventually resulting in a leak. Problems were intensified if there was a crevice in contact with the agent; this could lead to crevice corrosion. A more careful control of the design of the welded joints or of the welding practice would minimize future problems. In several cases, the investigation allowed identification of high risk lots in the inventory--those which would be most sensitive to leaking--so that these could be more carefully monitored, or removed from the stockpile.

LASER PROTECTION

Laser Hardened Materials and Structures

In the early 1970s the Department of Defense embarked on an extensive high energy laser development program. The programs in all three services were directed toward exploiting the potential of high energy lasers as weapons. Navy ships provided large platforms with huge amounts of electrical power being available. High Energy Lasers (HEL) have the advantage of virtually zero time of flight and the ability to deposit large amounts of energy onto incoming missiles. This new class of weapons was of great interest to fleet commanders interested in protecting their vessels. The Air Force developed the Airborne Laser Laboratory (ALL). The ALL was an airborne high energy laser demonstration program. It was capable of destroying missiles and various structural airframe components. The Army had demonstration programs such as the Mobile Test Unit (MTU), a lightly armored vehicle carrying a relatively powerful high energy laser. Additional demonstration platforms were developed to study the effects of LASER radiation on soft targets, i.e., electronic sensors, seekers and radomes.

By 1976 the Central Intelligence Agency (CIA) had accumulated a large database showing that the Soviet Union had a large well-financed High Energy Laser program and had destroyed helicopters and fixed wing aircraft in ground experiments. As a result, in early 1976 the Army Materiel Command approved AMMRC's use of exploratory development research funds to test and develop materials capable of withstanding attack from high energy laser radiation. The class of materials under study were called laser hardened materials (LHM). LHM are materials hardened against

electro-magnetic radiation rather than material surfaces that can be made hard by heat treatment using lasers as a source of heat. AMMRC formed a team of materials engineers, physicists, mechanical engineers and chemists. The team was drawn from various organizations at AMMRC.

Initial testing of helicopter components using megawatt carbon dioxide lasers revealed that bare metal surfaces reflected most of the laser radiation, but painted surfaces absorbed it. Painted surfaces which were under stress were especially vulnerable. Testing also revealed that electro-optical systems, optical surfaces and ceramic missile radomes were easily damaged by HEL radiation.

Vulnerability data generated by AMMRC, using large high energy carbon dioxide and chemical lasers, were shared with the weapons development community in all three services. This damage/ vulnerability test data served as a baseline to determine the cost effectiveness of the potential weapons. (It was always impressive to see how much damage could be done by these "invisible" beams but conventional bullets also do a lot of damage to these same targets if the target is hit.)

In 1978, the Departments of Defense of the United States, Australia and the United Kingdom signed agreements to participate in cooperative research in the area of laser hardened materials. An extensive program was conducted between AMMRC and the Materials Research Laboratory, Melbourne, Australia to utilize the 30 kilowatt laser at MRL to test and evaluate materials and structures fabricated by AMMRC. This program was one of the most successful international agreements ever signed and resulted in very significant contributions to the laser/materials effects database for the U.S. DoD.

By the mid 1980s an extensive "effects" database on materials had been developed. It was evident that each of the three services had specific issues to deal with due to the nature of their mission. However, AMMRC had a very close working relationship with the Naval Research Laboratory (NRL) and the Air Force Materials Laboratory located in Dayton, Ohio.

As a result of the close cooperation and data sharing among the three services, the limited funds were spent efficiently by each of the three services. The results at AMMRC were impressive. High temperature carbon-carbon metal bearing resins were tested and new materials of this class were developed that could be applied to surfaces that were then subjected to extremely high intensity radiation with little or no damage. Composite structural materials were designed to withstand intense heat while under load. The structures work opened up ways of providing alternate load paths through the structure to withstand thermal stress.

In the late 1980s it was apparent that HEL would not be very effective as a weapon used against hardened ground based targets. However, soft targets (human eyes) were very vulnerable to low energy laser (LEL) radiation. AMMRC, in conjunction with Natick

Laboratories, began testing dyes, specifically designed and recommended by industrial sources, for protection against visible and near visible laser radiation. The results of Watertown's accelerated environmental testing using state of the art environmental test chambers that subject test samples to extremes in temperature, humidity and light intensity, were useful in operation "Desert Storm." Although target designators and low energy lasers were not used as blinding weapons in the conflict, the Army and Marines had eye protection available. MTL had established the "useful lifetime" of the Laser Protective Spectacles used by our soldiers in Desert Shield/ Desert Storm and recommended to the Army, new and more conservative procedures for wearing and storing these spectacles in the desert environment. These procedures were implemented into the Army protocol, and our troops were assured of having adequate eye protection at all times in Saudi Arabia and Kuwait.

The contributions made at Watertown in the area of laser hardened materials are summarized as follows:

- A new class of metal bearing resin compounds was developed that can resist high intensity laser radiation.
- A methodology for providing alternate load paths for structures under both mechanical loading and laser radiation was established.
- The effective time of environmental exposure that laser protective dyes can withstand was established.

METAL MATRIX COMPOSITES

Metal matrix composites are metals, such as aluminum, reinforced with high strength, high stiffness continuous fibers, whiskers (single crystal fibers) or particulates. They have outstanding potential for cost-effective Army applications because they combine very high specific strength (strength/density) and modulus (modulus/density) with elevated temperature capability that is unattainable by monolithic materials. The properties can also be "tailored" to provide composites with unique characteristics, e.g., laser resistance and controlled thermal expansion.

The Army's MMC program began as a modest effort in 1964 at WAL. It focused on the development, evaluation, and utilization of sapphire (Al_2O_3) and silicon carbide (SiC) whiskers as strengthening agents for aluminum. Sesile drop tests were used to determine the wetting, bonding and interaction of molten aluminum on single crystal SiC and Al_2O_3 plaques. This was followed by the fabrication and evaluation of small experimental composites. It was found that when SiC and Al_2O_3 whiskers were fully infiltrated by and bonded to aluminum, they yielded composites which very closely approached reinforcement efficiency of continuous fiber reinforcements. This work provided the

foundation for a new technology known as whisker technology.

Although techniques were developed for the relatively low cost production of SiC whiskers from rice hulls, fabrication costs associated with the unidirectional alignment of these whiskers in a metal matrix were prohibitively expensive. This discouraged extensive work in this area. However, low cost silicon carbide and aluminum oxide particulates were also found to significantly reinforce aluminum alloys. Although this strengthening was much less than that of their whisker counterparts, sufficient improvements in strength, stiffness and wear resistance were obtained to make them an important class of MMC's for tank, automotive, aircraft, missile and small arms applications.

The advent of ultra high strength, high stiffness boron and carbon fibers added a new dimension to this effort. Pioneering studies on the melting and bonding of graphite fibers to magnesium resulted in the fabrication and evaluation of the first graphite fiber reinforced magnesium composite. Patent no. 3,888,661 dated June 10, 1975 was awarded to Watertown investigators for this development. It was then demonstrated that alkali metals could be used for treating graphite fibers so that they were wet and infiltrated by molten metals. Patent no. 4,157,409 dated June 5, 1979 was granted for this innovation. Multiple necking of tungsten fibers in a brass matrix was demonstrated and elucidated. The paper describing the work, published in Metallurgical Transactions, June 1970, was selected by the AIME-New England Regional Conference as one of the top seven papers by the New England Regional authors published by AIME in 1970.

Investigations into stresses in MMC's due to fiber-matrix thermal expansion mismatch; into the development of aluminum I beams selectively reinforced with graphite/aluminum; and into the acoustic emission of graphite and boron fiber reinforced aluminum during deformation and fracture all contributed to a growing understanding of these composites.

Major interest in these materials was generated in 1978 by Dr. Ruth Davis, Deputy Under Secretary of Defense for Research and Engineering (DUSDRE) in her Keynote Address to the DoD/Materials Technology Conference, February 21, 1978, which designated metal matrix composites as a major technology thrust of the Department of Defense. Following her address, the Army, Navy and Air Force were requested to prepare and present technology, management and funding plans to the DUSDRE to develop and use MMC's to meet their specific needs.

The Army Plan prepared at AMMRC focused on the research, development and application of MMC's to helicopter transmission cases and to combat bridging. This five-year plan, dated October 1978, was presented to DARCOM, DA and DUSDRE and was the first to be approved and funded under the MMC thrust.

The Army's MMC Program began in May 1979 when funds were received by AMMRC. This program evolved into two well-coordinated efforts: Army aircraft and combat bridging. The

helicopter transmission case program was a cooperative effort involving the Applied Technology Laboratory, Ft. Eustis, VA, selected contractors (Boeing Vertal, DuPont, DWA Composite Specialties) and Ft. Rucker, AL. It was coordinated with DARCOM, AVRADCOM (St. Louis, MO and Moffet Field, CA) and Department of Army Materials and Acquisition Directorate (DAMA). The bridging effect was a cooperative program involving MERADCOM, selected contractors, DARCOM and DAMA. It was directed at fabricating and evaluating MMC bridge components such as beams and king posts. Although these bridging components were successfully fabricated and evaluated, their high cost made them less than cost-effective, at that time.

The aircraft effort was directed at developing a full-scale fiber-reinforced Mg forward main transmission case for the CH-47D helicopter, having increased stiffness with reduced noise, vibration and maintenance. Significant accomplishments by the aircraft Army industry team include: finite element analysis of transmission case vibration; fabrication and bench testing of Gr/Al doubler plates; and successful flight testing of Gr/Al doubler plates with noise reduction achieved and the finite element analysis verified. In addition, experimental transmission cases were fabricated from magnesium reinforced by FP, a continuous Al_2O_3 fiber produced by DuPont. Tests of these cases showed them to be superior in strength, stiffness, fatigue and resistance to stud pullout.

The entire Army MMC Program was closely coordinated with the DoD MMC Program through the DoD MMC Steering Committee which received progress reports from the three military departments, DARPA and NASA semi-annually.

Starting in the mid 1980s, the Army MMC program was broadened to include, in close collaboration with other Army commands, the design and fabrication of a number of MMC prototypes such as helicopter landing skids, engine shafting, antennas, missile components, armaments, armor and tank track shoes.

During the late 1980s MTL played a major role in the development of the first continuous silicon carbide fiber reinforced aluminum jacket for the 125mm XMN 25 MMC Cannon. Test firing demonstrated dispersion characteristics equal to or better than its steel counterpart. Concurrently, MTL was the first laboratory to study the ballistic characteristics of discontinuous particulate reinforced MMC's. Utilizing industrial metal working capabilities at Watertown, members of the Process Research Group demonstrated the ability to improve armor performance of aluminum MMC's through thermochemical processing. In the early 1990s, research on MMC's broadened to include intermetallic matrix composites (IMCs). MTL was the first to demonstrate the potential of discontinuous ceramic particulate reinforced intermetallic composite (IMC) as an armor candidate. At present, collaborative research efforts with universities and industries are in progress to develop low cost MMC's with better

ballistic resistance than conventional monolithic materials.

In summary, Watertown continually supported and contributed to the advancement of MMC technology. Research accomplishments from earlier studies in fiber matrix wetting, bonding, and interaction and processing provided a firm foundation for enhancing the cost effectiveness of MMC's for Army applications. ARL-MD has played, and will continue to play, a major role in the development of MMC's and IMCs that will contribute significantly to the Army's effort to lighten the force.

MECHANICS

Fracture Mechanics

The discipline of fracture mechanics owes much to Watertown researchers, in particular to the efforts of Reinner Beeuwkes, Jr., Joseph Bluhm and Oscar Bowie. Dr. Beeuwkes joined WAL in 1941 and formed the Army's first Applied Mechanics R&D activity, taking the fracture behavior of Army materiel as the primary focus of his group. He recruited a highly qualified team of researchers, including Bluhm and Bowie.

Their research sought explanations as to why critical structures (Liberty ships and Army ordnance) were failing catastrophically at stress levels considerably below those normally considered to be safe (small relative to yield strength). The early work focused on loading rate, temperature, corrosion and notch effects. The WAL work was pursued in concert with the leading researchers in the country, as evidenced by meetings such as the "Symposium on Prevention of Brittle and Low Temperature Failures of Steel Components" hosted by WAL in 1949.

The fracture research requirements expanded dramatically after World War II with the movement towards advanced (high strength/weight ratio) structural materials to meet the needs of aircraft, missile, rocket and space vehicle applications. The critical issues were the role of ductility and toughness in the regions of stress concentration which were recognized to be the sites of fracture initiation. It was known that the material in such regions was stressed far beyond the elastic limit, but it was far from clear as to why a structure under nominally low stress would fracture as a result of such localized plasticity. A major part of the research was devoted to developing definitions of ductility and toughness which were appropriate for the multiaxial, elastic-plastic, stress-strain conditions at the fracture initiation sites, and which were consistent with the perplexing size and geometry shape effects encountered in applications.

Beeuwkes and Bluhm pursued experimental facets of the problem using available mechanics of materials theory. Bowie concentrated on the problems associated with describing the

stress distributions near notches and cracks. He mastered the state-of-the-art techniques in applied mathematics (e.g., "conformal mapping") which allowed determination of the stress distribution in the complex geometrics of ordnance components.

The discipline of linear elastic fracture mechanics (LEFM) was born when Irwin found that Griffith's energy criterion for the onset of brittle failure could be expressed in terms of the amplitude of the stress singularity associated with the precursor crack-like flaw. It was precisely this parameter which Bowie had earlier highlighted in the description of the stress distribution of a radially cracked gun barrel. Most significant was the fact that he had developed a technique for the treatment of a reasonably broad range of geometries with flaws, so that Irwin's concepts could be immediately applied to the crucial problems of the day. His contribution can perhaps be best appreciated by remembering that mathematics at this time was pursued not with the aid of electronic computers, but with pencil, paper and the mechanical desk calculator.

LEFM was found to be an excellent methodology, providing a means to predict brittle fracture behavior once fracture toughness data was obtained. However, the LEFM defined fracture toughness parameter does not explicitly account for microstructural fracture mechanism or the intrinsic ductility parameters of the material. These important issues in ductile fracture and in materials development were the focus of the research done by Beeuwkes and Bluhm during this period. While LEFM served as a framework for fracture when plasticity was localized to a small region at the stress concentrator, they sought a broader criterion which would explain ductile as well as brittle fracture behavior. Out of Beeuwkes's line of research came a methodology which used the concepts of critical stress and ductility in an elastic-plastic fracture criterion. He correlated laboratory fracture data on the basis of these quantities, using state-of-the-art mechanics of elastic-plastic deformation at blunted flaws.

Bluhm pursued experimental research on the micromechanisms which accompany macroscopic plastic deformation of metals. In 1966 Bluhm published with Robert Morrissey the paper "Fracture in a Tensile Specimen" in the Procs. First Int'l. Conf. Fracture which proved to be a landmark contribution. Using a very "stiff" tensile machine they were able to pause in the test and probe the specimen with ultrasonics to detect the very first indications of fracture. They could then stop the test and section the specimen to observe what were the first stages in the fracture. In subsequent tests they could allow the fracture to proceed further before stopping and sectioning the specimen. This allowed them to experimentally map out the sequence of events which occur at the microscale during tensile fracture. Their observations concerning void nucleation, growth and coalescence leading to internal macrocracks and overall fracture have been cited extensively, both by experimentalists and theoreticians involved in ductile fracture prediction. Their work provided one of the

first experimental demonstrations that the ductile fracture of metals occurs by the nucleation, growth and coalescence of voids nucleated at microscopic precipitates or inclusions in the metal. Thus they and Watertown played a key role in defining one of the fundamental failure mechanisms of materials.

Mechanics of Composites

Introduction

From 1969 to 1991, AMMRC and its successor organization, MTL, made a number of major contributions to improved understanding of the mechanical behavior of composite structural materials, and pursued a number of significant programs aimed at the application of composites to Army materiel.

The program of research in structural mechanics of composites was fostered largely under the tutelage and encouragement of Joseph I. Bluhm, Director of AMMRC's Mechanics Research Laboratory from the late 60s until the late 70s when he retired from Government service.

This mechanics of composite materials program embraced the following thrusts:

- 1969-1985 Applications of fracture mechanics concepts to fibrous composites;
- 1970-1974 Impact damage response of composite sandwich panels;
- 1969-1975 Investigations of edge effects in composite laminates;
- 1972-1985 Analytical and experimental studies of mechanically fastened joints in composite structures;
- 1978-1985 Evaluation and development of test specimens for composite materials;
- 1980-1991 Investigation of mechanical behavior of fiber and particulate reinforced metal matrix composites.

In addition to the mechanics of materials R&D in composites, a number of application programs were conducted, in the areas of:

- 1977-1985 Applications of organic and metal matrix composites to portable Army bridging;
- 1982-1991 Applications of composites to lightweight artillery.

Highlights and pertinent results of these efforts will be described in the following paragraphs.

Mechanics of Materials Efforts

Applications of Fracture Mechanics to Composites: Members of AMMRC's Mechanics Research Laboratory made one of the earliest attempts to apply the concepts of linear elastic fracture mechanics to composite materials. Publications reporting the results of this work appeared in various Special Technical Publications (STP's) of the American Society for Testing Materials (ASTM) as well as in the Journal of Composite Materials. A major part of this effort was the development of compact tension specimens of the type originally used for measurement of plane strain fracture toughness in metals, for applications to composite laminates. The chief finding of this work was that because of their multidirectional load paths, composites tend to defeat catastrophic propagation of cracks that develop around sharp notches and other stress concentrations, even though composites are generally considered to exhibit brittle behavior in comparison with metals.

Impact Damage in Composite Sandwich Panels: In the early 1970s, AMMRC workers conducted some of the earliest combined experimental and analytical studies of impact damage in sandwich panels consisting of advanced composite skins together with honeycomb core structures. This work is reported in 1973 and 1974 vintage ASTM STP's and SAMPE publications.

This effort featured a novel analytic approach to solving the problem of contact between the sandwich panel surface and the spherical indenter representing the impacting object. In this approach the forces of contact were represented as a continuous distribution of point loads whose amplitudes were unknowns of the problem. Use of a truncated trigonometric series representation of the point loads allowed classical series solutions for the plate on elastic foundation representing the skin/sandwich core combination. A special method of truncation for the series representation of the loads due to Lanczos gave particularly efficient solutions to the problem.

In addition, the experimental effort showed that for sandwich panels, impact events can be adequately represented by static indentation experiments, and that peak loads produced by such static experiments produce damage levels which are similar to those produced by actual dynamic impact. Thus damage levels for a given impact force can be estimated by such static indentation tests, thereby avoiding the complications of dynamic experimentation.

Investigation of Edge Effects in Composite Laminates: Composite laminates are normally analyzed through concepts which imply that in-plane strains are uniform through the laminate thickness. This assumption breaks down near free edges of straight sided plates and at cutouts in composite structures, where equilibrium requires that three dimensional effects take place. AMMRC efforts in the early 1970s were among the earliest efforts to

deal with such effects, both analytically and experimentally. Closed form solutions were generated for the stresses in $\pm\theta$ laminates which made the trends with regard to arbitrarily large numbers of layers relatively easy to develop. In particular, for the grouped laminate it was shown that at the interface between the $+\theta$ and $-\theta$ groups of layers, the interlaminar shear stress approaches a logarithmic singularity, whereas for the mixed laminate the stresses for arbitrarily large numbers of layers are about the same as for two layers.

In addition to the stress analysis, an important innovation was the development of moirè full field experimental strain visualization methodology for validating the predicted interlaminar shear stresses in $\pm\theta$ laminates. The results of the moirè effort were described in 1973 both in AMMRC reports and in publications in the open literature journals such as Experimental Mechanics.

Additional experimental effort regarding the influence of free edge effects on failure initiation in $\pm\theta$ laminates was presented, which features high-speed photographic results showing the development of failure initiation cracks near free edges and generally confirming the analytic predictions with regard to the importance of the three dimensional stress state for this situation.

Analytical and Experimental Studies of Bolted Joints in Composite Structures: Through much of the 1960s and 70s, Oscar L. Bowie and colleagues were engaged in pioneering use of two-dimensional complex variable approaches to a number of significant stress analysis problems, especially in the area of the modelling of stresses around crack tips in situations applicable to fracture mechanics of isotropic bodies (see Fracture Mechanics in this section). Although the complex variable method had been available for some time, the major contribution of the AMMRC workers was to take advantage of the growing power of electronic computers in that period to treat highly complex geometries, especially those of stress concentrators (holes, notches, cracks and the like) in finite bodies, for which classical solutions had previously been intractable. It was a natural outgrowth of this effort to extend the complex variable stress analysis methodology to orthotropic elastic bodies as composite materials took on a significant role in structural systems.

As a result of this extension, AMMRC personnel developed a version of the complex variable approach for a particularly challenging aspect of composite structures, that of mechanically fastened joints. Whereas in metallic structures, detailed stress analyses are usually not sought because plastic behavior of the metal tends to make the stress state relatively uniform throughout the joint, in fiber reinforced structures, elastic behavior prevails through most of the deformation state to failure, and detailed knowledge of stresses around fasteners is needed for effective joint design. The detailed stress analysis

problem involves such complications as a lack of knowledge of the pressure distribution between the fastener and the plate against which it is bearing, the variation of the region of contact between the fastener and plate as the load varies, and the occurrence of a finite outer boundary to the body in which the fastener is present. The work of the AMMRC team in the 1974-1980 time frame appears to be the earliest reported efforts in which all such complications were taken into account.

Companion experimental efforts on the mechanical response of bolted joints were also undertaken. As in the work on edge effects in laminates discussed above, the moirè full field strain analysis approach played a major role in these studies. Through these efforts a number of important design principles for mechanically fastened joints were developed. Again, the moirè approach was based on facilities developed at AMMRC.

Of special interest was the work in the mid-1980s which featured development of a special finite element procedure for evaluating the behavior of mechanically fastened composites undergoing nonlinear response. Here the experimental results obtained from moirè approach were directly compared with the finite element predictions through the use of artificially generated moirè fringes within the finite element analysis.

Evaluation and Development of Test Specimens for Composite Materials: Considerable pioneering work was done in the AMMRC program on improved mechanical property test specimens for composite materials. This included improved tension test specimens and the pioneering adaptation of the Iosepescu shear test specimen to composite materials.

New understanding of the performance of tension test specimens for composite materials was provided by combined finite element and experimental studies of conventional specimens which had been developed over the years for composite materials. In particular, the role of stress concentrations in degrading the effectiveness of these conventional specimens was clarified analytically and demonstrated experimentally. More important, the AMMRC work described a new principle for defining ideal (so-called "streamline") specimen shapes in composite materials for eliminating such degrading stress concentrations. In the latter effort, extensive analytical and experimental effort was conducted to demonstrate the success of the streamline specimen shape in providing superior performance. Again, the role of moirè full field strain measurement was instrumental in providing a clear understanding of the principles on which the streamline specimen design was based.

Of a similar pioneering nature was AMMRC work representing the first known use of the notched plate developed by Iosepescu for shear strength measurement in metals to composite materials. In particular, the AMMRC work showed that the Iosepescu specimen was as applicable for measuring in-plane shear strengths of composite materials as it had been for metals, and that the

specific details (relative dimensions) of the Iosepescu specimen developed for metals could be directly applied to composite materials. Again, this work included analytical work based on finite element studies for delineating the theoretical principles of the specimen design together with experimental effort based on the moirè approach to demonstrate the validity of the theoretical effort.

Development of Special Finite Element Capability: Instrumental in many of the efforts involving combined experimental and analytical studies of composites was a high performance finite element capability developed on a continuing basis from about 1973 to 1994. This was probably one of the earliest finite element codes to be completely graphically driven, and to provide automated mesh generating and post processing capability. Among the efforts which made use of this capability were those on mechanically fastened joints, on tension test methods, and on shear test methods for composites.

Application of Moirè Methods to Composites: As indicated in the previous discussion, extensive use was made over the years on moirè strain measurement capabilities developed by Prof. F.K. Chiang of the State University of New York at Stony Brook. Prof. Chiang was instrumental at AMMRC in development of two alternative approaches to application of moirè methodology, that of the use of cemented specimen gratings and a non-contact method based on optical processing of laser speckle. For composites, the lower sensitivity cemented grating approach was generally successful. Moirè strain measurement was an important part of the efforts on edge effects in composite laminates, on mechanical response of bolted joints in composite structures, on behavior of tension test specimens and on shear test methods for composites.

The non-contact laser speckle approach which was pioneered by Prof. Chiang, was adapted to Army facilities in the period of 1974-1990. This method, which was considerably more sensitive than the cemented grating approach, had the benefit of avoiding the need for attachment of gratings to the test specimen. The method was well suited to experimental verification of fracture mechanics analyses of crack propagation in metals, and provided, in particular, a method for evaluating the effectiveness of bonded composite repair patches for suppression of crack growth in metallic structures.

Structural Applications of Composites

A number of major programs aimed at application of composites to Army materiel were undertaken by AMMRC/MTL/ARL over the years. Major efforts by Watertown include the Army Composite

Bridging effort and the Lightweight Army Howitzer effort.

Army Composite Bridging Program: The Army bridging program was initiated at the request of Ft. Belvoir in 1978, in response to a need for lightened portable bridging capable of being transported by vehicles available to the Army at that time. The AMMRC program included: 1) design and fabrication of a filament wound graphite epoxy box beam structure for use as a pre-launching rail to be emplaced over gaps to be traversed following which the bridging structure was to be installed by rolling across the launch rail; 2) design and fabrication of a lower tension member for a folding assault bridge consisting of a 24' long x 2' wide x 5/8" thick graphite epoxy/aluminum sandwich plank together with articulated end fittings; 3) development of friction joint concepts for use as attachments to bridging components in which elimination of stress concentrations provided potential for greater structural efficiency than is available with conventional bolted joints.

Army Lightweight Howitzer Program: The Army lightweight howitzer effort was a program conducted at Picatinny Arsenal with the objective of development of a towed 155 mm howitzer of substantially reduced weight in comparison with the 16000 lb M198. A lighter 155 mm howitzer would permit helicopter deployment by combat organizations not having air transport resources required for the M198. The Picatinny effort involved parallel design and development of three competing lightweight howitzer concepts. The AMMRC/MTL lightweight howitzer effort provided consultative support on composite materials to the Picatinny program, in addition to demonstration of application of advanced materials to selected generic towed howitzer components. Design, fabrication and static structural test efforts were carried out which demonstrated the feasibility of applying organic matrix composites to the cradle (supporting structure for the gun tube) of the M102 105 mm howitzer. Additional effort was carried out to design, fabricate and install filament wound roll-bar components on the M102, representing a weight reduction of about 70% over existing steel roll bars (over 200 lb for the steel roll bars vs. 45 lb for the composite items). Other design efforts were carried out to evaluate metal matrix concepts for weight reduction of the lower carriage of the M198 howitzer.

Computational Mechanics Research on Elastomers

In the mid 1980s, major concerns developed over the poor service life of tank rubber track pads on the M1 main battle tank. The pads are made from filled elastomers, a viscous rubber-like material. The large strain viscoelastic stresses

found in these materials could not be accurately modeled. As a result, a research program was established at Watertown to develop improved constitutive models for these materials. Several topics were addressed: 1) techniques which model viscous large strain incompressible material behavior; 2) methods for obtaining material constants in elastically stable material laws from experimental data; and 3) modeling of fracture in thick elastomer components.

The Finite Element Method, FEM, is a numerical method which predicts structural and material behavior. The geometry of a structure or load carrying component is discretized into elements to create a finite element model. Based on laws of physics and mechanics, the elements contain mathematical descriptions of material and structural behavior. For rubber, special elements must be used to model the nearly incompressible nonlinear material behavior. Watertown researchers developed an improved axisymmetric FEM for rubber-like materials. Their element formulation introduced a new approximation method which uses two configuration mappings to simplify the mathematical computation of principal strains, a critical part of the computations for the analysis of rubber.

When elastomers are subjected to rapidly applied large strains, which are then held constant in time, their stresses relax with time. Experimental tests demonstrate that the relaxing component of the stress varies nonlinearly with respect to the applied strain. This nonlinear viscous stress effect can often be predicted by superimposing stresses derived from a rubber energy density function, which is forced to relax in time, to the stresses used for modeling the static deformation. The superposition method was well established in the literature, but the available methods did not contain a complete three dimensional formulation that could be used to construct an efficient FEM for rubber. As a result, the linear, small strain, Maxwell internal solid theory for viscoelasticity was extended at Watertown to a full three dimensional nonlinear internal solids theory. This new theory, called Viscohyperelasticity, utilizes the same material test configurations as those used for determining the nonlinear static material law. The method of adding a relaxing energy function to determine nonlinear viscous stresses can also be mathematically formulated with a pointwise internal variable theory. Such a nonlinear viscoelastic model was derived which utilizes stretch ratios as the internal variables.

Material laws are mathematical models of how a material's stresses relate to its strains. A material law is stable if it produces an increase in the material's internal energy when external work is done on the material. Experimental tests commonly used to characterize rubber material behavior include uniaxial tension and compression, biaxial tension, and shear. A material law based only on tensile data often does not predict compressive, biaxial tension, and shear data well. In addition, many experimentally determined material laws are unstable at

strains outside the range of strains covered by the tests even when they are based on several modes of deformation. A method for selecting material constants which assures stability in the case of the classical Rivlin material model was developed at Watertown. The method involves constraining the regression analysis that fits the Rivlin material model to the data. It has been applied to determine material laws for triblend elastomers, natural rubbers, styrene butadiene rubbers, nitrile rubbers and polyurethanes.

Experimental studies of fracture are typically confined to thin specimens. Because track pads and other Army load carrying components are thick, research was performed to investigate the failure process in this geometry. A short, thick, cylindrical dumbbell, test specimen was designed to examine the fracture process experimentally. A deep notch was introduced along the mid-height of the specimen, which was then loaded in tension. Experimental observations revealed a process of localized material failure above and below the fabricated crack tip, followed by delamination and stable crack growth in the load direction. This process was continuous and repetitive until ultimate material failure. A theoretical model of fracture in thick elastomers was developed on the basis of these experiments and explains the toughness exhibited by these materials.

Finite element analyses of cracks in thick sheets of rubber were also conducted. The sheets were loaded in tension. The analyses confirmed the presence of a theoretical nonlinear asymptotic solution for rubber materials and characterized the load amplitude parameters associated with this solution. The results of the studies indicate that material close to the crack tip underwent large rotations in addition to large deformations, predicting a bluntness observed experimentally. Stresses were largest close to the surface of the crack, suggesting that localized material failure should initiate above and below the crack tip. Finally, a potential region, where cavitation was likely to occur, was identified. Inside this region, the shape and orientation of nucleated microvoids was predicted. These results are consistent with experimental findings.

The technology developed in this computational research program has been successfully utilized. Finite element analyses of track pads were completed. The Naval Underwater Systems Center used the stable material algorithm to help evaluate polyurethane materials which were being considered for a prototype launcher system. The NASA Langley Research Center is using a modified version of the stretch ratio internal variable model to simulate viscoelastic composite material behavior in aircraft tires. Fracture in the M-1 roadwheel's rubber coatings has been modeled to better understand the mechanisms of failure observed. Interaction with other government agencies, academia, and industry supported and strengthened the program.

History of the Lightweight Steel Tow Bar System

As a consequence of the introduction and development of the M1 Abrams Main Battle Tank and the subsequent upweighted M1A2, traditional tank tow bar systems have proven insufficient in terms of strength and unreliable in terms of survivability.

The U.S. Army Tank and Automotive Command (USATACOM) recognized this deficiency and elected to sponsor a Technical Demonstration Program with ARL-MD (then MTL). The focus of this program was to exploit the advantages of high strength lightweight composite materials applied specifically to the tank tow bar recovery system. Failure rates for the current tow bar system in both M60 and M1 tank recovery operations averaged approximately 120 failures worldwide per month.

Phase I program plans resulted in Watertown negotiating a development contract with Foster-Miller Inc. of Waltham, Massachusetts. The objectives of the program were to design and fabricate components for two prototype tow bar systems. Each system would consist of two identical filament wound graphite tubes with Kevlar skins for abrasion protection. Individual tubes were fitted with high strength steel alloy (SAE 4340) endfittings at both ends for attachment to the towing provisions of the "dead" tank and the pintle (tow hook) of the towing vehicle.

A characteristic feature of this design included identical and fully interchangeable tow bar legs. This feature, in contrast to the current tow bar system, was intended to enhance the recyclability of damaged tow bar systems in an effort to extend the usable life of components. Incidental advantages of this feature included simple disassembly for manually transporting and installing the system piece by piece by a single recovery crew member. Armored units could further exploit this design by issuing "half systems" to each tank. Recoveries could then be conducted by combined inventories of the "dead" and responding tanks as opposed to relying on specialized recovery vehicles being dispatched from distant field maintenance depots.

Laboratory testing of the prototype tow bar tubes verified the success of this design. Tensile and compressive yield strengths in excess of 360,000 pounds per tube were attained while simultaneously reducing system weight from 340 to 210 pounds, a 38% weight reduction.

Successful laboratory tests resulted in advancing the evaluation phase of the program to field tests conducted at Aberdeen Proving Grounds. Tow bar systems instrumented to emit strain and temperature response signals were used to tow 70 ton M1A1 tanks across modified cross country courses and fresh water marshlands. Performance results of these tests indicated the tow bars operated well below their rated tow load capacity.

Documented performance results were forwarded to USATACOM for sponsor evaluation. Upon review, the M1 Abrams Program Management Office elected to continue the program and requested that attempts be made to optimize the system with an emphasis on high strength, reduced weight, low cost and toughness in terms of

ballistic and collision survivability.

Watertown responded to this request and submitted a proposal to fabricate prototype tow bar systems made entirely of high strength steel alloys (SAE 4130 tubes and 4340 endfittings). The proposed design included the interchangeable leg feature and optimized the dimensions of components with regard to failure by buckling and yielding. The complete steel alloy system was rated for loading up to 360,000 pounds and weighed only 260 pounds, a 24% weight reduction compared to the current tow bar.

A test program, identical to that outlined for the composite tow bar system, was undertaken in both the laboratory and the field. Performance of the system exceeded expectations, thereby resulting in the issuance of a limited Safety Release (document authorizing use by military personnel).

Extensive field evaluations were conducted by U.S. Army units assigned to Fort Riley, Kansas. Prototype tow bar systems designated for Fort Riley recorded over 1,500 miles of actual disabled M1 tank towing service. Additional tow bar systems were issued to units of the Vth Corps headquartered near Frankfurt, Federal Republic of Germany under the sponsorship and guidance of the Army Materiel Command's Field Assistance in Science and Technology (AMC-FAST) program advisors. Watertown's participation in this program afforded engineers and designers the opportunity to obtain user feedback prior to finalizing the design. The exceptional performance, low cost of manufacturing, and reduced weight of the steel alloy system convinced USATACOM to initiate replacement of the current tow bar system with the lightweight Watertown design.

Currently, USATACOM is soliciting bids for manufacturing the ARL-MD tow bar system. Manufacturing is planned to commence in the Fall of 1996 for issuance as standard equipment on the M88A1 HERCULES Recovery Vehicle. Replacement of obsolete systems will take effect at the discretion of USATACOM and as inventory levels permit. A final demonstration program requested by the AMC-FAST office was conducted with elements of the Eighth U.S. Army, South Korea, during the month of July, 1995.

WELDING

Watertown has made a number of significant contributions to welding and joining technology over the years. These contributions have not only enhanced the survivability and mission readiness of a variety of Army vehicles and systems, but have also advanced the state-of-the-art for the American industrial and scientific communities. Contributing to this record of achievement have been the excellent characterization, analytical, non-destructive testing, and other scientific staff and facilities at Watertown.

The aims of welding R&D at Watertown were two fold: first,

to solve problems that faced the Army in the manufacture of materiel, and second, to develop new welding processes so that they could be used in the joining of metals and alloys.

The story starts in the 1920s with Watertown's development of all welded gun carriages. The manufacture of gun carriages in a wide variety of sizes over the years (from field artillery to antiaircraft guns to disappearing carriages for large coastal defense guns) was a major activity of the Arsenal. Prior to the 1930s these were made from castings. Watertown engineers realized the savings that would accrue from welded fabrication, but welds in the early 1920s were not accepted as being reliable enough for a structure which is subjected to shock loading.

In the late 1920s Dr. Horace H. Lester had demonstrated the efficacy of the application of radiography to the control and improvement of foundry processes (see Early Years and the section on NDE). This same approach was applied to improving welding technology, i.e., using radiography coupled with other tests, including ballistic impact, to assess the quality of welds made under carefully controlled and documented procedures. This culminated with the acceptance of welding as the preferred method of fabrication. Watertown later transferred its expertise to the Navy and industry. ASM counted the use of welding for the fabrication of gun carriages as one of the major milestones in the development of metallurgy in America in the period 1917 to 1948.

In the 1950s Watertown also made significant contributions to the welding of titanium as part of its titanium development program (see the Early Years). A problem was immediately encountered in the first attempts to weld titanium and its alloys. During the welding process, gases from the atmosphere would diffuse into the weld, causing the resulting joint to be brittle. Watertown developed shields that would cover the metal being joined with inert gas that would protect the metal being joined from the atmosphere until the weld had solidified and the temperature of the surrounding metal had cooled so that the gas in the atmosphere would not be absorbed by the metal. This development vastly extended the possible use of titanium and its alloys. In the 1970s several MM&T projects were carried to develop diffusion bonding of titanium as an alternate approach to fusion welding.

Another major area to which Watertown contributed was the welding of armor steels. These materials are a challenge to weld because of their higher hardenability (they form martensite readily on cooling from the welding temperature) and hardness. Both factors make them susceptible to hydrogen induced cracking. Watertown research examined factors such as reducing hydrogen sources, the type of filler alloy, the composition of the shielding gas, and pre- and post-weld heating. Significant contributions were made to MIL STD 1941 - Metal Arc Welding of Homogenous Armor. The common weldability tests for armor materials, such as the H plate and cruciform tests were developed by Watertown.

In the late 1970s and the 1980s and extending into the

1990s, numerous studies related to the welding of armor steels were carried out. These studies ranged from very fundamental studies of the mechanism of hydrogen absorption into the molten weld pool to: developmental studies of factors seeking the most economical shielding gas to use; approaches to stud welding; the effect of cutting processes; procedures to weld ultra-hard ESR4360 steels for the Blackhawk crew seat (see applications of ESR steel); weld cracking of the Light Armored Vehicle (LAV); and automation of the welding process. In addition, studies of the weldability of a new aluminum armor alloy 2519 were also conducted. Some of these are briefly described below.

Hydrogen Absorption Model: Previous investigations had postulated that hydrogen was absorbed into the center of the welding pool directly as the diatomic molecule H_2 . Researchers at Watertown and MIT in the late 1980s showed that a more probable model was that the hydrogen molecule dissociated into two single hydrogen atoms in the arc and were absorbed at the trailing edge of the weld pool. This model won the award the most significant contribution to welding research in the year it was published.

Hydrogen Assisted Cracking Modes in High Strength Steel Welds: In another fundamental study in the late 1980s the stress intensity which causes crack propagation in high strength steel weldments was quantified as a function of the hydrogen content at the crack location. This relationship was used to assess previously developed theoretical mechanisms for hydrogen assisted cracking. These mechanisms included: planar pressure, surface absorption, dislocation pile-up, dislocation transport, and microplasticity. It was found that the microplasticity model best described how the stress intensity factor and hydrogen content affect the modes of intergranular, quasi-cleavage, and microvoid coalescence fracture.

Shielding Gas Used in the Welding of the M-1 Tank: This project was initiated in 1986 to find a lower cost alternative to the expensive, patented weld shielding gas mixture used at the Lima Army Tank Plant in fabrication of M-1 Tank hulls and turrets from armor steel plates. The project was conducted cooperatively with the Land Systems Division of General Dynamics which produces the M-1 for the Army and operates the Tank Plant. A wide variety of weld and shielding gas mixtures were evaluated with the objective of reducing cost while maintaining welding performance. Criteria used in the evaluation included: weld metal deposition rate, amount of hydrogen in the weld, weld bead profile, amount of spatter, and of course, gas cost. Variables besides gas composition included: weld voltage, electrode stick out, base

metal composition and nozzle geometry. Mechanical and ballistic test of welds were also carried out. As a result of the study, General Dynamics switched to a less expensive 95% Ar/5% O₂ gas at the plant with cost savings of approximately \$1 million per year.

Automation: Watertown in the mid 1980s developed, in conjunction with the U.S. Army Construction Engineering Research Laboratory (CERL), a weld quality monitor based on optical emission spectroscopy. When an energetic ion in the welding arc plasma decays to a less energetic state, it emits characteristics radiation which can be detected using spectroscopy. A method to detect the amount of hydrogen present in the arc and to use this to control production welding conditions was developed. This system was patented and licensed to National Standard for use in their Arcon II arc weld monitoring system. The U.S. Navy Programmable Automated Welding System (PAWS) uses this sensor system as does General Dynamics Land Systems Division.

Light Armored Vehicle Support: In the late 1980s and early 1990s there was a concern that the Marine Corps' LAV had a problem with an excessive number of cracks. The LAV was fabricated from light-gage high hardness steel armor (MIL-A-46100) above the beltline to maximize protection against AK47 ball ammunition. This was one of the first uses of high hard armor in a welded structure. Although the LAV was a Marine Corps Vehicle, the program manager for the LAV was based at, and supported by, the Army's Tank Automotive Command. The PM-LAV requested that MTL undertake a study to determine the cause of cracking, to examine weld repair procedures, and to recommend approaches to minimize cracking in current and any future vehicles.

MTL carried a detailed study and review of a number of factors that might be contributing to the problem including: analysis of cracked components; mechanical and ballistic properties of samples of the steel armor; and extensive examination of plate cutting and welding. The plate cutting studies examined the cut edge for the thickness of untempered martensite (brittle) and the width of the heat affected zone for the following cutting processes: water jet, abrasive wheel, plasma-arc (air and under water), carbon-arc (air), oxyacetylene, and laser. Of the higher speed methods, laser cutting was recommended to give the best cut edge.

The welding work examined: welding procedures, repair procedures, vehicle production and repair welds, failed weldments and weld components and the weldability of the MIL-A-46100 armor steel. In addition, a 2nd and 3rd Echelon Welding Repair Handbook for the LAV was prepared at the request of the PM-LAV for use as an aid in repairing cracks in existing vehicles.

Summary: Welding plays a significant role in the wealth creation of any industrial civilization. Base materials must be joined in order to create value added products, ranging from soldered circuit boards to cars. Watertown's role in combat readiness has had a number of spin-offs into the private sector to enhance the lives of everyone. In addition, Watertown's welding engineers have provided significant assistance to the commodity commands and depots by suggesting, consulting with, and approving changes in design and fabrication methods and materials. Numerous specifications and standards have been streamlined and harmonized with industrial standards to lower the cost of manufacturing. Alternative manufacturing methods and procedures have saved millions of dollars.

CORROSION

Corrosion Research

In 1966, AMRA proposed the theme of Corrosion-Induced Fracture and Control for the Advanced Research Projects Agency (ARPA) Corrosion Coupling Program. Yale University, Syracuse University, TRW, Inc., Union Carbide, and AMRA comprised the coupling team. The ARPA program was open to all Department of Defense Agencies having an interest in the general area of Corrosion. The topic of Corrosion-Induced Fracture, embracing the influence of environment on the nucleation of a crack and its subsequent propagation, was proposed by AMRA because it was the least understood and most catastrophic cause of all failures. Of concern were all aspects of failures, including crack initiation, crack propagation, and fracture of high strength steels, titanium alloys and aluminum alloys. This was especially true in connection with the utilization of these recent high strength-to-weight materials which are used in designs with marginal safety factors.

The Army had direct experience with several dramatic examples of catastrophic failures attributable to corrosion-induced cracking. Failure of a rotor socket of an Army combat helicopter resulted in several personnel fatalities and loss of the helicopter. Failure analysis performed by AMRA demonstrated that this corrosion-induced fracture caused the failure. Several failures of steel pressure vessels of the hydraulic accumulator system of a missile resulted in destruction of the missile during storage. Investigation by AMRA revealed that the extremely brittle nature of the steel, coupled with a corrosive environment, resulted in brittle fracture and catastrophic failure of the vessels. There were numerous other cases of failure of missiles and low flying aircraft where corrosion and stress teamed up to destroy military personnel, materiel and equipment.

AMRA was the only Army laboratory selected as one of the finalists. (Other Army proposals were submitted.) But the Naval Research Laboratory proposal on Stress Corrosion Cracking was finally selected (an Air Force proposal was also submitted) only because they already had in place a large, fully-staffed and funded laboratory devoted to corrosion. Nevertheless, the AMRA proposal received commendation from ARPA as well as from all levels of the Department of Defense. Subsequently, AMRA, in light of the ARPA experience, formally established a Corrosion Research Branch which to this date carries out a proactive successful corrosion R&D program, responding to Army needs (even at a transitional location at Johns Hopkins University before moving to the new ARL laboratory at APG, MD). Important accomplishments achieved during the period 1970-1995 are highlighted.

High strength steels are used in Army aircraft systems for their high specific strength and their ballistic resistance. Typical aircraft applications include the AH-64 (Apache) helicopter mixer support bolt and main rotor blade pitch links. These steels are susceptible to hydrogen embrittlement when heat treated to yield strength levels close to 240 Ksi. Significant load is usually placed on these high strength components and many are exposed to environments, which in combination provide the necessary requirements for Stress Corrosion Cracking (SCC)/Hydrogen Embrittlement (HE). Six of these steels heat treated to hardness values of Rc 51-53 were studied for susceptibility to SCC/HE (4340 ESR, Aermet 100, C-250, T-250, C-300, 4330). The SCC/HE resistance of these steels was found to be a function of the open circuit potential of the steel. The critical concentration of hydrogen in the steel for crack initiation is also a controlling factor in determination of SCC/HE resistance. Further studies on the effects of potential step polarization (varying the applied potential) and hydrogen overpotential (the amount of hydrogen available to diffuse into the steel) demonstrated that the crack tip responds rapidly to changes in the hydrogen activity. Step polarization, the ability to arrest and restart crack propagation by stepping the applied potential, was demonstrated. This proved that the critical stress intensity threshold for hydrogen-assisted cracking, K_{ISCC} , is a direct function of the hydrogen overpotential at the crack tip.

Titanium, because of its attractive high strength-to-weight ratio and good general resistance to corrosion, continues to be a prime candidate for many Army applications (aircraft, gas turbines, tactical vehicles). Unfortunately, many of its alloys have been reported as susceptible to SCC in a variety of environments. Watertown's early pioneering research on metallurgical effects (producing different microstructures) on the electrochemical behavior of titanium alloys has become a standard reference for subsequent research. The stress corrosion behavior of titanium alloys is also influenced by microstructure. The SCC susceptibility of the Ti-8Al-1Mo-1V alloy (used in the

compressor section of gas turbine engines) was studied in the mill anneal, beta STA, and alpha + beta STA conditions. Solution treatment temperatures which increased the amount of martensite increased the SCC resistance of the alloy in aqueous media. Beta and martensitically transformed beta regions exhibited ductile characteristics whereas the alpha phase failed by a brittle cleavage mode. Because of this difference in phases, the heat treatments employed that changed the amount and morphology of the alpha and beta phases also influenced the susceptibility of the alloy to SCC. It was also shown that electrochemical measurements (pitting potentials) correlated with SCC results. Further, study of a newer beta alloy, solution-treated and aged Ti-3Al-8V-6Cr-4Mo-4Zr, which was a candidate for Army vehicle torsion bar applications because of its superior spring rate characteristics, demonstrated that the alloy was immune to SCC in aqueous sodium chloride solutions (marine atmosphere).

Aluminum-Zinc-Magnesium alloys, such as 7039 and 7075 have been used in Army vehicles and aircraft, particularly for lightweight armor. For equal protection, these alloys show greater weight savings over steel as the angle of attack approaches normal and the velocity of the projectile increases. The greater thickness provides a much stiffer hull or turret structure, allowing weight savings by eliminating bulkheads and stiffeners. In an effort to obtain a better understanding of the effect of different precipitate and dislocation distributions in the matrix on the stress corrosion susceptibility of the 7075 alloy, different matrix microstructures were introduced by combinations of tensile deformation and heat treatment. It was shown that solute segregation to grain boundaries might have a more significant effect on the stress corrosion cracking of aluminum alloys than had been believed. Further study showed that the stress corrosion threshold stress intensity decreased from 15 ksi $\sqrt{\text{in}}$ to 3 ksi $\sqrt{\text{in}}$ as the solution annealing temperature increased from 740°F to 980°F. Also, increasing the solution treatment temperature reduced the amounts of minor alloying element (Cr, Mn) intermetallics and developed higher strengths in the alloy on aging. Generally, changes in solution treatment temperature affects the stress corrosion susceptibility of the alloy in a complex manner through their effect on the grain boundary composition and the metallurgical microstructure.

The Army's experience with magnesium aircraft components has shown that significant corrosion problems exist which require increased maintenance, impacting both cost and readiness. It is clear that improved protective schemes are needed to provide corrosion resistant magnesium components before magnesium's inherent weight advantage can be fully utilized. In a cooperative program with Sikorsky Aircraft, several advanced alternative treatments were assessed and compared to the current practice for protecting magnesium. Electrochemical Impedance Spectroscopy (EIS) provided a reliable estimate of the film integrity and corrosion protective capability of the protective schemes evaluated. There was good correlation between the EIS

and conventional salt fog exposure data. Several of the advanced protective schemes performed better than the currently used system which employed an environmentally unacceptable chromate pre-treatment. These data were provided to Sikorsky Aircraft to complement their fatigue, oil exposure, strippability and touch up test program. These developments in coating technology are expected to yield large-scale savings and enhance the effectiveness of the Department of Army mission.

Also, electrochemical impedance spectroscopy (EIS) and salt fog exposure were employed to evaluate whether a non-chromate conversion coating for aluminum alloys could be a suitable replacement for the currently used chromate conversion coating (environmentally unacceptable) without compromising corrosion resistance. The non-chromate conversion coating generally compared favorably with the standard chromate treatment, used singly or in combination with a primer and topcoat. Field testing is required before this environmentally acceptable conversion coating can be recommended as a reliable alternative to the currently used chromate conversion coating.

Power systems are a priority item in terms of required research and advanced development for producing military equipment with greater performance potential. Current thrusts in developing advanced military gas turbine engines seek to reduce fuel consumption with engines of smaller size, lighter weight, lower cost and greater reliability. Performance improvements and cost reductions can be achieved by the development and application of new alloys and processes. Advances in superalloy solidification procedures have resulted in the development and use of single-crystal superalloys. Since the single crystal alloys do not require alloying elements to provide grain boundary strengthening, their compositions are different and less complicated than their polycrystalline counterparts. The oxidation resistance of several single crystal superalloys in air at 2000°F were compared to a polycrystalline alloy under both isothermal and cyclic conditions in a simple tube furnace. The oxidation resistances of all the single crystal alloys were superior to the polycrystalline alloys. In order to simulate more closely conditions in a gas turbine, similar studies were performed in a dynamic burner rig at 2000°F. Also, to simulate deposits which form on the surfaces of turbine hardware, specimens were coated with sodium sulfate (Na_2SO_4) which forms in the gas turbine environment from sulfur in the fuel and salt from soil and/or water.

The single crystal alloys again had better oxidation resistance than the polycrystalline alloy. The single crystal alloys probably can be used uncoated for applications involving oxidizing conditions and temperatures below 1650°F. But all of the alloys were severely degraded when a liquid sulfate deposit was placed on their surfaces at 1300°F and 1650°F (hot corrosion). All of the alloys under these conditions would require a corrosion coating. Subsequent coating studies

demonstrated that platinum- modified aluminide diffusion coatings always performed better in cyclic oxidation as well as hot corrosion than the conventional aluminide coating.

Coated refractory alloys are also candidate materials for advanced Army gas-turbine engines. A modified disilicide composition for both tantalum and columbium alloys provided oxidation protection for 200 hours at temperatures between 1700°F and 2700°F in furnace tests at Watertown. Unfortunately, disilicides do not afford protection in the intermediate range 1400°F to 1600°F, where they may fail due to the phenomenon commonly called pesting. This leads to the rapid disintegration of the bulk material to a voluminous heap of powder ("pestring"). Watertown's investigation showed that a simple pre-oxidation treatment of the complex disilicide at a temperature of 1900°F (above the pesting temperature) eliminated pesting. This treatment has been adopted by leading coating researchers and vendors.

Environmentally Acceptable Materials Processing

Many of the treatments and processes used to mitigate corrosion contain some type of environmentally hazardous constituent. For example, hexavalent chromium (Cr+6), is a carcinogen that is currently on the EPA's "top-ten" list of hazardous wastes that are targeted for reduction. Hexavalent chromium can enter the waste streams of many surface treatment processes, including cleansers, etchants, conversion coatings, anodizing treatments, paint dyes, and chrome electroplating operations. Other notable surface protection processes that can produce hazardous wastes include: cadmium electroplating, adhesive bonding, painting and paint stripping with high levels of Volatile Organic Chemicals and cleaning/degreasing with Ozone Depleting Chemicals.

Watertown first became involved in research for environmentally acceptable materials and processes in 1988 as an outgrowth of work performed by the Corrosion Center of Excellence (CTX). From its inception in 1985 following guidance from General Richard H. Thompson, CG, AMC, the CTX was responsible for overseeing the Army's corrosion prevention and control procedures. The Center of Excellence performed corrosion surveys at field units and depots worldwide. Through the CTX's work with AMC, Watertown became aware of the breadth of the environmental challenges faced in the corrosion community, as well as the widespread corrosion problems faced by Army units.

Watertown's involvement in the Environmentally Acceptable Material Treatment Processes (EAMTP) began with programs to utilize ion-implantation as an alternative surface hardening/corrosion prevention treatment. The EAMTP effort under the MANTECH (Manufacturing Technology) initiative was also established during General Thompson's command at AMC. Though

ion-implantation has not been extensively used for corrosion prevention (it has been incorporated successfully into cutting tool treatments), this program led Watertown into the field of Pollution Prevention.

From this beginning, the corrosion group has continued to make significant contributions to various Army pollution prevention efforts. The corrosion group has worked to implement IVD aluminum as an alternative to cadmium electroplating in applications for both armored vehicles and helicopters. One current program initiated in 1993 focuses on elimination of both electroplated chromium and cadmium by physical vapor deposition (PVD) and ion assisted processing techniques. Another effort is directed towards implementing non-chromate conversion coatings for aluminum alloys in Army systems.

Current trends indicate that the future will bring even more stringent environmental requirements, reductions in operating budgets, and the need to extend the service of current weapons systems and materiel beyond their designed service lives. These will focus even more importance on the Army's need for effective and environmentally friendly corrosion prevention and control measures, and the corrosion group intends to remain at the forefront of research in this area.

Corrosion Prevention and Control Program

The Army's corrosion prevention and control program received four-star emphasis when Gen. Richard H. Thompson, CG, AMC, gave the keynote address at the 1985 Tri-Service Conference on Corrosion, which was hosted by MTL in Orlando, Florida. In that address, he said, "Today's technologies offer the best hopes ever for waging a successful war on corrosion." General Thompson thus set the tone not only for the conference but for the Army's new initiative to respond to the pervasive and continuing problems with environmental degradation of air and land vehicles, munitions, electronics, missiles, and support equipment which were recognized as being a serious global liability in both decreasing material readiness and in significantly increasing life cycle maintenance costs.

General Thompson followed this up with his Commander's Guidance Statement 94. In that statement he listed six steps to be taken to reduce the burden caused by material corrosion and deterioration. One was the establishment of a Center of Technical Excellence for Corrosion Prevention and Control. Other initiatives to be undertaken were: corrosion-free equipment designs; more effective maintenance; improved corrosion-prevention and control training; and increased awareness about corrosion control.

In accordance with Commander's Guidance Statement 94, MTL was designated as the Army's Center of Excellence for Corrosion Prevention and Control (CPC). This mission assignment

acknowledged the Laboratory's long-standing leadership within AMC in the technologies of metallic corrosion and organic structural materials deterioration, and carried with it a high-profile responsibility to reduce the estimated \$2 billion annual cost of corrosion to the Army.

The CPC Center of Excellence (CTX) was to: serve as a central operations and information base; ensure cross-fertilization of corrosion prevention technology and sharing of lessons learned; coordinate development of model CPC programs with AMC's major subordinate commands; promote CPC awareness and training efforts; guide the allotment of resources to effectively accomplish the objectives of the CPC program; and maintain very close ties with industry to ensure mutual exchanges of the latest CPC technology. Again, to quote General Thompson, "We feel this alignment will provide a better focus for strengthening the technology base, for facilitating technology transfer, and for ensuring the best possible return on our R&D investments." It was estimated that a 25% cost reduction of the \$2 billion due to corrosion and deterioration could be achieved by using current state-of-the-art corrosion/deterioration control technology. In addition, a proactive RDT&E program was needed to develop new and improved corrosion resistant materials and coatings. Recent examples of cost savings by implementation of corrosion prevention and control programs show the magnitude of what can be accomplished. For instance, implementation of recommendations for just one Army helicopter saved \$32.4 million, while avoidance of faulty stripline circuit production in an Army missile saved \$4.0 million. MTL received a commendation for its contributions to these efforts.

Also, an aggressive series of initiatives were implemented, including:

- An AMC wide network of CPC action offices was established and activated to capture/resolve corrosion problems in current fielded systems and to prevent such problems in future systems under development.

- Army civilian CPC training by the MTL Materials Technology School was introduced and CPC sections were incorporated in several Army training manuals.

- CPC CONUS and OCONUS Surveys by CTX and MSC Action Officers with unit personnel were conducted in order to identify corrosion problems and to recommend appropriate corrective actions.

- An Army CPC Data Base was established and CPC Awareness actions undertaken, including the publishing of the Army Corrosion Digest Quarterly, specific issue videotapes (e.g., AH-65 Corrosion Problems), workshops and conferences on various CPC technical concerns.

- Army CPC policy coordination was introduced and implementation effected with senior Army military and civilian executives. AR 750-59 on CPC was published in August 1989. Tri-service Corrosion coordination was promoted via workshops and biannual conferences. An Army-Navy CPC workshop was organized

and conducted in Hawaii to establish joint Army-Navy CPC coordination there.

Despite all these efforts, the Army CTX was forced to close in 1991 when the downsized budget of MTL could no longer subsidize this operation and the long promised funding from AMC HQ did not materialize. The closing of the CPC CTX was indeed unfortunate since corrosion continues to be a devastating and ubiquitous enemy to Army materiel worldwide. Although no Armywide coordinated counter attack on corrosion has existed since, a significantly increased level of awareness of corrosion and how to deal with it does exist in the Army today.

SIGNIFICANT ADVANCES IN NONDESTRUCTIVE EVALUATION

A history of nondestructive evaluation at Watertown without crediting Dr. Horace Lester's innovative radiographic research in the 1920s and 1930s at the Watertown Arsenal would be incomplete. Dr. Lester's first-in-America industrial radiographic testing facility provided the impetus that created the nondestructive testing industry. In addition, he developed the approach in which radiography was used to develop and improve foundry manufacturing procedures so that quality could be obtained by proper manufacture rather than by rejection of improperly made parts (see Industrial Radiography). This led by two decades the Total Quality Management approach made famous by Deming. This concept of building quality in was next applied to development of the welding process in a pioneering effort to demonstrate that gun carriages could be reliably fabricated by welding instead of casting. The use of radiography as a method for steel foundry control and the all-welded gun carriage were cited by ASM as two metallurgical milestones in "Metallurgy in America, 1917-1947."

Because of the positive results achieved in the radiography field, Watertown Arsenal was the natural selection as the site for the development/advancement of other nondestructive testing methods: ultrasonics, magnetic particle, liquid penetrant, eddy current and neutron radiography. In 1925, Dr. Lester provided the first X-ray diffraction measurement of residual stress in a component. It was the first diversification of a nondestructive evaluation method--progress which would cause like-minded scientists after him to query about other nondestructive evaluation methods, "What else can it do?"

World War II provided the impetus for the development of an offshoot of Magnetic Particle inspection--the Magnetic Recording Borescope (MRB)--whereby the gun tube is magnetized and a magnetic tape reading head is used to detect magnetic flux leakage fields around cracks or other shallow flaws. Thereafter, the Korean and Vietnam Wars generated the need for MRB Models II through VIII as in-process inspection aids as well as field testing units for gun tubes up to 175 mm. (For more on this, refer to the paper on the NDE of Gun Tubes in the Armaments

section.)

Ultrasonic Spectroscopy was discovered in the early 1960s and introduced to the world in 1965. Ultrasonic Spectroscopy utilizes the conversion of time-domain ultrasonic signals to frequency-domain ultrasonic signals by means of Fourier transforms. This approach is based on the Fourier principle that time-dependent functions such as ultrasonic pulses are associated with frequency spectra. In ultrasonics, this type of conversion can be used to determine the frequency-dependence of sound losses in materials, the frequency-selective reflectivity from internal flaws, and the thickness resonances provided by back surface reflections. The equipment used in Ultrasonic Spectroscopy is identical to that used in many usual pulse-echo instruments with the addition of an electronic time gate and a spectrum analyzer. Its application to nondestructive testing includes:

- Thickness gaging of components, particularly of components with rough surfaces such as is found in corroded items.
- Determination of microstructure by measuring the attenuation of the sound as it passes through the material and thereby determining the average grain size.
- Determination of defect geometry based on the fact that defect configuration rather than size is the cause of variations in echo amplitudes.
- Angle-Beam Testing by specifically delineating differences between rounded, flat and L-shaped defects.
- Detection of delaminations due to the significant variation in pip amplitudes based on the location (layer) of the delamination.

In the late 1960s, the Army had a problem with determining if M43 primers contained the proper amount of explosive. A research team believed that neutron activation analysis could solve the problem. The fast neutrons generated by an in-house neutron generator would activate the nitrogen and oxygen in the azides and nitrates in the primer into very short half-life radioactive isotopes without activating the metals in the compounds. The amount of oxygen and nitrogen, and hence the amount of the azides and nitrates, could then be determined by counting the radiation emitted as the oxygen and nitrogen isotopes decayed to their normal states. It was demonstrated in the laboratory that this could be done successfully. It was possible, therefore, to carry out 100% nondestructive inspection of the pellet weight in the M43 primers on an automated line at a high rate. In 1970, the members of the team received an Army R&D Achievement Award for their work.

In 1973, a new nondestructive evaluation method--Acoustic Analysis--was used successfully in the inspection of silver soldered brazed joints in ammunition, crack detection in 81 mm mortar shells, crack detection in ceramic personnel armor shields, and flaw detection in welded overlay bands on 155 mm M-483 projectiles.

Until 1974, radiography was considered to be far ahead of ultrasonics in its usefulness and desirability due to the fact

that ultrasonics relied upon a handheld transducer and provided a difficult oscilloscope interpretation. Radiography offered a pictorial image upon completion and was not dependent upon an operator's variable hand pressure to produce the image. The most significant advancement that could make ultrasonics competitive and that could be made in a short span of time was to improve the output display. AMMRC personnel surveyed the medical ultrasonics field and found that vast strides had been made in the previous fifteen years. To update their system, AMMRC personnel incorporated a 64-element transducer into a medical ultrasonic unit that had been modified and adapted with a scan converter, expanded television display, and recorder printout. The result allowed both B- and C-scan data to be prepared. The B-scan printout provides a side view to illustrate the depth of a flaw beneath the inspection surface and to indicate in which scan path the flaw is located, but does not furnish its precise point along the scan path. The C-scan printout provides an overhead (or plan) view to illustrate the x-y position of the flaw as a projection on the inspection surface, but does not indicate the z position, that is, how far beneath the surface the flaw can be found. The two scans complement each other by yielding the exact locations and dimensions of all flaws. The system was later outfitted with computer interaction for data processing, signal analysis, and transducer control.

In 1974, a project called AIDECS (Automatic Inspection Device for Explosive Charge in Shell) was launched to produce automatic inspection equipment that could measure the melt-pour charge in 60,000 105-mm shells per day. An X-ray tomographic system was developed in conjunction with the Armaments Research and Development Command for this purpose. Within the equipment, the decision making was automated, thereby eliminating film and film interpreters. The system was incorporated into an innovative automated melt-pour process at Lone Star Army Ammunition Plant, TX. In 1980, the system was tested and demonstrated that it could perform as intended. Plans were being made to scale-up the system to accommodate 155-mm shells. It was estimated in 1980 that this system would save the government 3.5 million dollars per year after installation at a shell loading plant.

Additionally in 1974:

- A prototype instrument was developed which utilizes the principle of ultrasonic spectroscopy for the detection of voids in laminar products.
- Ultrasonic polarity and C-scan tests were used to inspect tank track pads--from the rubber side of the pad, making it feasible for field use--for unbond at the metal-to-rubber interface where, in addition to the unbond, corrosion was also detected.

In 1975, an ultrasonic C-scan procedure was developed for the inspection of the brazing of the rotating band on artillery shells. Of concern were cracks, craters, and unbonds. The new inspection reduced costs by eliminating the sampling destructive

testing. It further improved the inspection efficiency due to its 100% application. In 1976, the confidence in this inspection progressed to the extent that it became the acceptance test of all M-454 nuclear artillery shells manufactured in Watertown. (See the paper on Nuclear Munitions Prototyping in the Armaments section for Watertown's program of support for the PM Nuclear Munitions.)

Additionally in 1975 the use of glass fiber composites in modern missiles necessitated the development of reflectance Fourier infrared analysis and X-ray electron spectroscopy analysis to detect the onset, rate and type of deterioration in order to predict and prevent their weathering.

In 1976, the state-of-the-art X-ray diffraction procedure used to determine the relative amount of phases present in a powder mixture or a polycrystalline material was slow and required tedious measurements of many X-ray diffracted intensities, and the effect of texturing resulted in errors of 50% in the phase percentage as calculated from the X-ray intensities. Therefore, a convolution technique was developed to approximate the integrated intensity of an X-ray diffraction peak doublet from a measurement of its peak height and peak width. This new technique, together with a texture correction, was applied to the analysis of silicon nitride to characterize reaction-sintered and hot-pressed powders for optimizing processing parameters. Significant time was saved, and the error rate dropped to 5%, establishing this method as the most efficient means for phase analysis of silicon nitride with a potential for applications in many other materials areas.

Additionally in 1976:

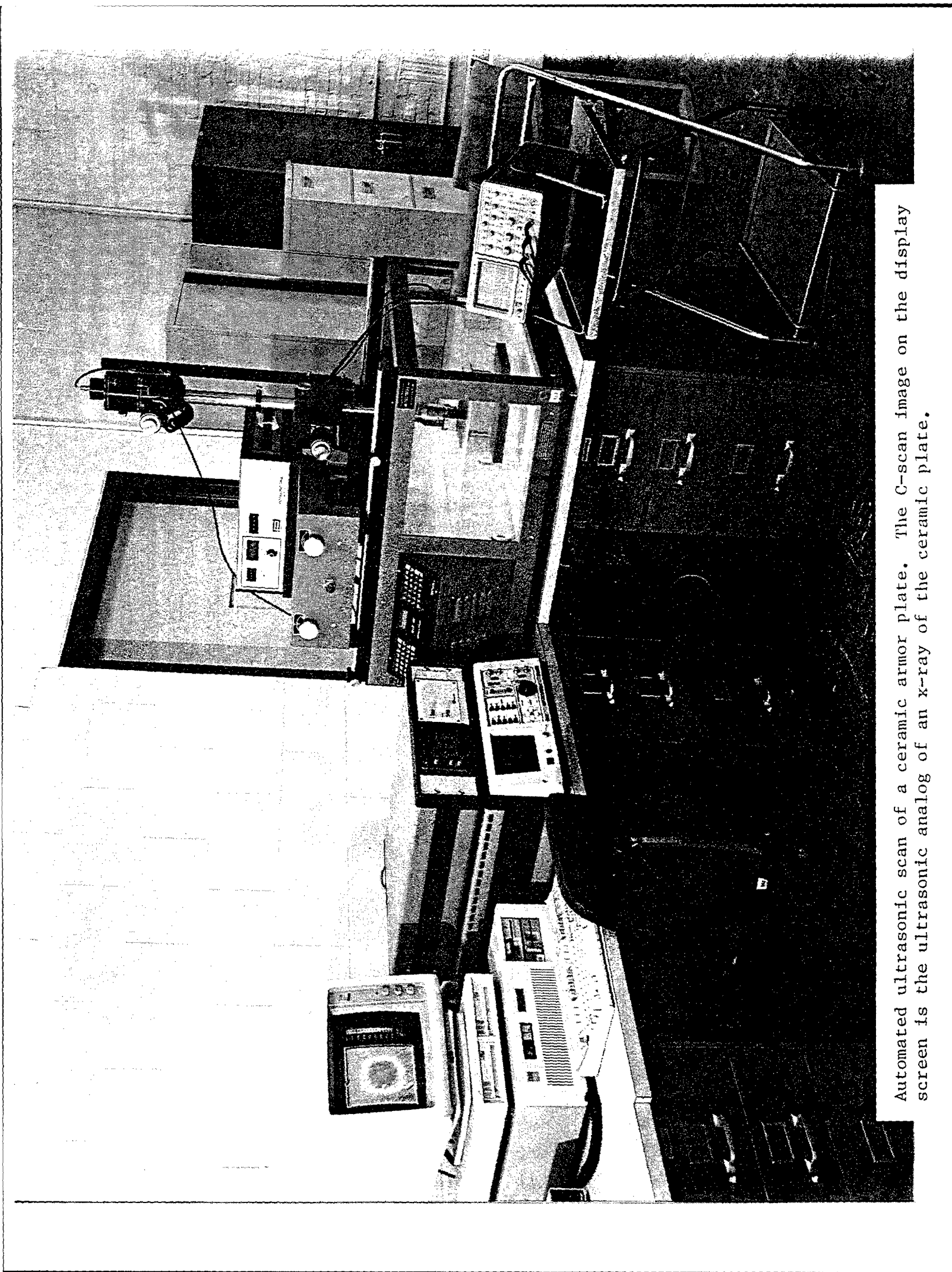
- Neutron radiographic capabilities were developed, utilizing a californium source. Problems with excessive gamma rays exposing the film were reduced by repositioning the source and by utilizing a single emulsion film. A superior neutron radiography image resulted.

- Various approaches were tried to unscramble complex ultrasonic signals in order to gain information about the nature and integrity of materials involved. One uses multicolored ultrasonic images representing specimen transmission characteristics obtained at various frequencies. Another interacts a laser beam with an ultrasonic beam to produce holographic images of internal defects.

In 1977, a computerized X-ray unit was developed which automatically maps the grain orientation of the shaped charge liners of armor-penetrating 105-mm HEAT-T-M456 rounds as they are being manufactured. Mapping the grain orientations provides a means for predicting the liners' ballistic penetrating ability which in turn reduces the need for continued test firings.

Also, in 1977:

- A sequentially-fired transducer array was designed and assembled to inspect, in a single shell rotation, the brazed and welded overlay copper rotating bands bonded to 8-inch rocket motor bodies while imaging the entire rotating band region. The



Automated ultrasonic scan of a ceramic armor plate. The C-scan image on the display screen is the ultrasonic analog of an x-ray of the ceramic plate.

ten-second test is considerably faster than the previously used single-crystal inspection time of three to five minutes. Also, a tank track pad and a graphite epoxy compact tension specimen were successfully tested in less than five seconds using this equipment.

- AMMRC and AVSCOM combined their efforts to produce a sophisticated computer controlled instrumentation system for the twofold purpose of using the magnetic flux leakage technique to detect subsurface defects in new bearing raceways and using the magnetic Barkhausen technique to measure residual stress in bearing components. The components under test are used in helicopter jet engines and power trains.

- Magnetic perturbation inspection equipment was designed and constructed that provides reproducible, high-sensitivity, high-speed, automatic nondestructive inspection of critical regions of artillery shells made from high-fragmentation steels.

From 1978 to 1983 the first on-off mobile neutron radiography system was developed as a collaborative effort between Watertown and Vought Corporation utilizing funds made available through the Army's Manufacturing Testing Technology Program. It had previously been agreed in the nondestructive evaluation field that neutron radiography would not be widely used unless and until a mobile unit was produced. The mobile neutron radiography system proved to be a rapid and accurate inspection tool in checking aircraft for moisture in honeycomb sections and for debond in laminated areas--inspections which would otherwise require additional hours to provide potentially less reliable information.

In 1978, an infrared technique was developed under contract for the Navy for flaw detection in a multi-layered steel-reinforced rubber composite component of a critical structure.

In 1982, an advanced ultrasonic testing instrument was designed, fabricated, and tested which brought together several technologies to produce a high-speed nondestructive testing instrument which reduced the inspection time for certain products such as artillery shell rotating bands by a factor of about 10. The equipment is fully automatic and does not require a trained operator to determine the part's acceptability. The individual responsible for this advance received an Army R&D Achievement Award in 1982.

In order to meet the needs of the Army relative to its utilization of advanced composite materials in systems such as tactical bridging components and helicopter rotor blades and fuselage sections, AMMRC developed, in 1983, field portable inspection systems using ultrasonic and vibrothermographic techniques to test for delamination and separation in large composite structures. Also, a unique field portable neutron radiography inspection system for composite structures was built. It is comparable in size to an X-ray system and is of particular value in the investigation of adhesively bonded metallic and composite materials and in revealing corrosion, trapped water, and leaked fuel in aircraft without disassembly.

In 1984, as part of the ceramic armor development effort, X-ray diffraction and ultrasonic imaging techniques were developed to monitor ceramic armor quality. This improved ability to monitor the quality of ceramic tiles at Watertown strongly contributed to the development of lower cost ceramics for which several Watertown researchers received Army R&D Achievement Awards in 1987. Also, under the Manufacturing Testing Technology Program, a contact ultrasonic C-scan system was developed which does not require immersion of the test item and requires access to only one side. This system costs 60% less than a comparable immersion system.

In 1985, success was achieved in developing and corroborating a technique for the unambiguous detection of fatigue crack nucleation during cyclic loading. The new method involves electronic detection, utilizing flux leakage field measurements, of magnetic field perturbations resulting from a local change in magnetic properties where no surface discontinuity existed--only a plastic zone. The new technique is useful in the detection of the onset of fatigue damage in steel specimens.

In 1986, a project was undertaken to characterize ceramic and composite materials using ultrasonic velocity C-scans utilizing a time intervalometer as the primary instrument component. A time intervalometer is a modified ultrasonic thickness gage that measures the time interval between any two signal amplitudes that exceed a set threshold. The operator selects the two signals (e.g., top surface and the first back reflection, or the first and second back reflections) that are to be compared. The instrumentation has a 0.001 micro-second time resolution and an accuracy within ± 0.002 micro-second. The method can be used for shear and longitudinal wave time-of-flight C-scans and for C-scans of materials with nonuniform thicknesses. Variations from longitudinal to shear wave involve tilting the specimen to the desired angle in a through transmission immersion setup. For materials with nonuniform thicknesses, two pulse-echo transducers are set facing each other in an immersion tank. The water distance is measured. The specimen is placed between and normal to the transducers. The new water path is subtracted from the full path to determine material thickness. For ceramic materials, longitudinal wave velocity C-scans clearly display local elastic modulus changes with some quantitative information derived. It is more reliable, quantitative, and sensitive than the previously used radiographic method. For composite materials, fiber volume variation is clearly displayed with repeatability using velocity C-scans.

Eddy current research began with the evaluation of its capabilities to reveal material properties such as conductivity/resistivity, alloy, heat treatment, permeability, grain size and structure, and structural integrity. Research in the late 1980s investigated, with positive results, the ability of an innovative computer program intimately linked with eddy current test equipment to provide a three-dimensional eddy current image

whereby the inspection probe could not only pinpoint the surface location of the flaw, but could also provide its depth beneath the surface.

Throughout the history of Liquid Penetrant as an inspection method, Watertown personnel have experimented with and compared new products as they arrive on the market. As the base is closing, a project is continuing with the objective of determining which currently allowed cleaner performs most like the now-banned CFC-based cleaners. In another new application, in 1993, a penetrant was introduced into a ballistically tested composite structural armor plate to assist in the radiographic determination of the lateral damage caused by the projectile. The area into which the penetrant seeped became more opaque to the radiation and showed up lighter on the resultant radiograph. A further advance in the inspection of this type of damage was made by using a Computerized Axial Tomography scan (CAT scan) to image in detail the damage in the plate. The CAT scan effectively sliced the plate laterally into several extremely thin layers and displayed the extent of damage in each slice. This allowed the damage to be tracked as it developed during the penetration event.

A crowning achievement to Watertown's preeminence in NDE came with the founding of the Department of Defense Conference on Nondestructive Testing, the first conference being held at Watertown Arsenal in October 1951. The founder was Carlton H. Hastings, chief of the Nondestructive Testing Branch at Watertown from 1939-1957, who in concert with Warren Inglis of Frankford Arsenal pursued ways to eliminate duplication of test efforts. This conference, hosted each year by a different branch of the service, is a meeting of engineers, scientists, technicians and managers from all Commands and DoD/Government Activities who have the responsibility for development or application of NDT methods in research, engineering, maintenance and quality assurance.

The defined purpose of the conferences has been the coordination of the development and application of nondestructive testing and inspection methods to materials and assemblies for the Department of Defense. Objectives have been threefold: to facilitate the dissemination and exchange of information pertaining to nondestructive testing methods and applications; to provide a forum for the attack and solution of selected inspection problems of the military; and to foster uniform application of nondestructive testing methods.

In another demonstration of Watertown's leadership role in NDE, in 1964, the Department of Defense recognized as operational the Nondestructive Testing Information Analysis Center (NTIAC) of AMMRC. This operating center was then officially established within the framework of the DoD Scientific and Technical Information Program as the DoD Center for the Analysis of Nondestructive Testing Information.

The mission of NTIAC is to collect, maintain and disseminate information in the field of nondestructive testing. Information is collected from technical reports, the open literature and

other sources and is stored in a rapid retrieval system. By 1995 over 50,000 citations were in the database. NTIAC also prepared critical reviews, monographs and other publications on the state-of-the-art in selected areas of nondestructive testing.

The Department of Defense transferred full responsibility for operation of the NTIAC to a private contractor, Southwest Research (San Antonio, TX), in 1976. Until 1984 technical monitorship of the NTIAC contract was provided by MTL. Thereafter, Watertown assisted the Office of the Undersecretary of Defense, Research and Engineering in the monitoring of the contract.

The NDE Branch's application of nondestructive testing and inspection methods to the material development programs at Watertown has significantly enhanced those programs. Watertown's role in the dissemination and exchange of NDE information has made it a leader in DoD materials problem-solving attempts.

BASIC RESEARCH

Polymer Science at Watertown

The early years of polymer science at Watertown involved research into the application of polymeric materials as armor materials. The performance of polymeric materials was improved by taking maximum advantage of the strength of the polymeric chain in its preferred direction, employing this principle, for instance, in the development of laminated armor material using thin films of highly oriented polymer film. Such a material, known as "XP," was used in the field for applications where lightweight armor was needed to defeat fragmentation weapons (see Stretch Polypropylene Radar Transparent Armor). The same principle of maximizing properties by maximizing polymer chain orientation was also used to fashion lightweight composite materials of superior ballistic properties, consisting of high-performance synthetic fibers in an organic matrix. Followup work in this direction resulted in the development and use in the field of the Kevlar-reinforced composite infantry helmet (see Personnel Armor for Ground Troops).

In a different direction, research was conducted on the somewhat exotic phosphazene polymers, in which a chain of alternating phosphorus and nitrogen atoms replaces the predominantly carbon backbone of the polymer (see Polyphosphazenes section). Fibers, films, fluids, and coatings composed of such polymers, proved their usefulness in specialized applications where their good resistance to fire is essential, such as electrical insulation in a confined vehicle. Another successful application from this family of engineering polymers was in the area of fireproof transmission fluids.

Finally, improved engineering elastomers were developed for

applications in two separate areas with demanding requirements: for the tank track pad, where mechanical durability and resistance to heat buildup is of interest; and for chemical protection applications, such as protective clothing, where resistance to liquid and/or gas permeation is of the utmost importance. New formulations of urethane elastomers, extending the envelope of the mechanical and thermal properties of elastomers, were developed to deal with the tank track pad problem. For protective clothing applications, efforts were made to combine the elastomeric properties of the polyurethanes with the barrier properties of polyolefins via the development of urethane elastomers with polybutadiene or polyethylene. In this way advantage was taken of the chemical inertness of polybutadiene or polyethylene to exclude chemical agent molecules from the rubbery matrix. Such formulations were evaluated for such chemical protection applications as gas masks.

Finally, the chemical protection work was extended to the direct modeling of the diffusion process of agent molecules in rubbery polymers using molecular dynamics. This approach, involving the multiple recalculation of forces, positions, and velocities of a thousand individual atoms in response to thermal vibrations, is very demanding in terms of computer time used, even on the fastest machines. For this reason, the computer program was modified to run on the KSR-1 massively parallel supercomputer. With these modifications and on this computer a factor of 75 speedup was attained, making future work in this area more practical.

Polyphosphazenes

Introduction

A continuing search by the Army for new elastomeric materials with a service capability over a wide temperature range (-70° to over 400°F), and for improved fire-resistant elastomers and plastics to meet the requirements of the Department of Defense was the basis of Watertown's technological interest in polyphosphazenes. Polyphosphazenes are ring or chain compounds consisting of alternating phosphorus and nitrogen atoms with various halogen or organic groups attached to the phosphorus atom.

The polyphosphazene program at Watertown started as a joint venture with the Army Natick Laboratories. Natick had supported work in the 1960s to develop elastomers with better fuel resistance and low temperature performance for Arctic applications. Preliminary evaluation of phosphazene rubber at Natick demonstrated the excellent potential of this material for the Army's low temperature rubber requirements.

Phosphazenes 1969-1980

The polyphosphazene rubber effort was transferred from Natick to Watertown in 1968 with the formation of the new organic materials group at Watertown. Since virtually all known elastomers, plastics and fibers were organic polymers, a number of questions emerged concerning these new inorganic polymers; very little was known at that time about polyphosphazenes. The decision was made at Watertown by the Chiefs of the Fibers and Polymers Division and the Organic Materials Laboratory to start an in-house research program on polyphosphazenes, which would accelerate the development of this new class of inorganic polymers for the Army.

During the period from 1970-1980, Watertown established a polyphosphazene synthesis and characterization program, which contributed significantly to a more thorough understanding of the factors controlling the preparation, thermal behavior, chain structure and other fundamental properties needed for the technological development of these polymers. Watertown researchers characterized some of the first phosphazene fluoroelastomers prepared by the Horizons, Inc. group in Cleveland. A synthesis program established at Watertown became the basis for a number of studies on the structure-property relationships of polyphosphazenes.

The phosphazene elastomer development efforts at Watertown during this period included cooperative programs with Natick, the Rubber and Coated Fabrics Group at Fort Belvoir, Rock Island Arsenal and the Naval R&D Center at Annapolis. The initial focus was on Arctic fuel-handling equipment, but as work progressed, interest expanded to include O-rings, oil seals, obturator pads, fire-resistant cable coatings and flexible foams. Contract work with Horizons expanded to include both the phosphazene fluoroelastomers for the Army and phosphazene aryloxyelastomers for both the Army and the Navy. The Navy was particularly interested in the aryloxyphosphazene elastomers for fire resistant foams and wire coverings for submarines and surface ships. As contract work progressed from exploratory development to prototype development, the program was further expanded to include Firestone Tire and Rubber Co. Commercialization of polyphosphazenes was realized by 1980, when Firestone introduced the polyphosphazene fluoroelastomer under the trademark, PNF. Firestone subsequently introduced the phosphazene aryloxyelastomer under the trademark, APN.

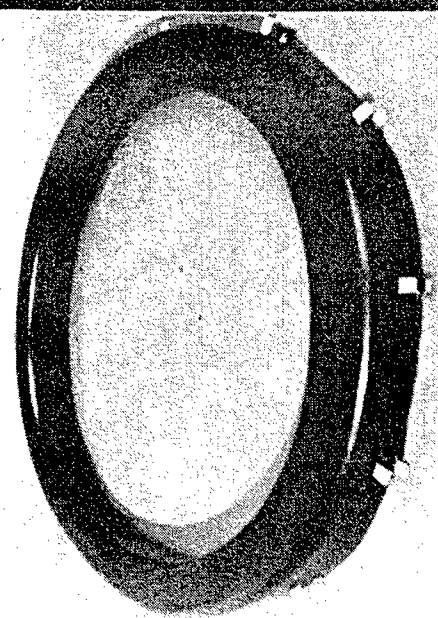
Although the initial goal of the Watertown-Army phosphazene program was for fuel handling equipment, the first Army application of this new material was in the M-1 tank. In the late 1970s, problems arose with the air cleaner assembly for the gas turbine engine of the M-1 tank. Dust and sand ingestion was a particular problem with the gas turbine engine. An air filter system was designed for the engine, but conventional rubber seals were not acceptable for the application. An improved rubber

PHOSPHAZENE POLYMERS



Phosphazene Fluoropolymer
155 mm Obturator Pad

Phosphazene Fluoropolymer Fuel Hose
For Arctic Service



- Low Temperature Flexibility
- Fuel and Oil Resistance
- Fire Resistance

Current Application
Air Plenum Seal of Phosphazene
Fluoropolymer For M-1 Tank Engine

OTHER ARMY APPLICATIONS

- Coated Fabrics For Collapsible Fuel Tanks
- Transmission Seals
- O-Rings For Hydraulic Systems
- Fire Resistant Foams and Wire Insulation

plenum seal was urgently needed for the air filter assembly. Plenum seals were fabricated using the phosphazene PNF rubber, successfully field tested, and approved for specification in the M-1 tank. No other rubber had the low temperature flexibility, flexural fatigue resistance, tear resistance, and fuel and oil resistance needed for this critical application. If it had not been for PNF, fielding of the M-1 tank might have been delayed. Thus the 1970s ended with successful adaptation of polyphosphazenes into an Army system.

Phosphazenes 1980s-Early 1990s

With the successful commercial development of polyphosphazene elastomers, the phosphazene program at Watertown shifted into another phase in the 1980s. The in-house expertise, which was now well-established and internationally recognized, served to advise both government and industry on requirements for improved high performance elastomers. Ethyl Corporation obtained the commercial interests in phosphazenes from Firestone and further developed phosphazene elastomers under the trademarks Eypel-F and Eypel-A for the fluoroelastomers and aryloxyelastomers, respectively. Ethyl Corporation interacted extensively with Watertown in matters pertaining to both the research and potential government markets for phosphazenes.

The phosphazene research program during this period was directed towards fire resistant fluids, polymerization mechanism studies, liquid crystals/nonlinear optical polymers for laser eye protection and fire resistant matrix resins for the lightweight structural composites that were being introduced into Army combat vehicles.

Watertown worked closely with the Naval Surface Warfare Center in Annapolis to develop cyclic phosphazene fire-resistant fluids. The work was successfully transitioned into a Navy-industry program, which prepared over 200 gallons of a phosphazene fire-resistant fluid for evaluation in the hydraulic systems in Navy aircraft carriers. This technology was also made available to the Army for fire-resistant fluid and lubricant requirements in combat vehicles.

Watertown scientists made important contributions to understanding the mechanism of the ring-opening polymerization of hexachlorocyclotriphosphazene to poly(dichlorophosphazene). A better understanding of the process was crucial for sustaining the future success of phosphazene technology. Several papers were published in this area and a patent received, which helped to solidify the recognition of Watertown for its role in phosphazene chemistry.

A third important contribution during this period was in the field of liquid crystalline polymers. In April 1987, at the American Chemical Society national meeting, Watertown researchers announced the preparation of side-chain liquid crystalline

polyphosphazenes. This important development expanded the area of liquid crystalline polymers to a new class of materials for consideration as non-linear optical (NLO) polymers and other electro-optical devices. Cooperative efforts were established with Natick Labs and the Navy at China Lake to evaluate these new liquid crystal polymers for device applications.

Other phosphazene cooperative programs were established with NASA-Langley for fire-resistant matrix resins, and with Natick and UMass-Lowell to develop a new class of electrorheological (ER) fluids. While progress in these areas has been limited, the possibility remains that phosphazenes can be developed to improve the fire-resistance of structural composites for combat vehicles and as ER fluids for smart materials.

Summary

The Watertown polyphosphazene program established important working relationships with both the government and industrial interests, as well as with leading academic scientists. Without the early Watertown support, phosphazene development would have been set back at least five years. Many national and international cooperative R&D efforts were established. Several national and international meetings were organized and sponsored in conjunction with the American Chemical Society, Office of Naval Research, the Naval Surface Warfare Center-Annapolis, and the Army Research Office, addressing the many facets of polyphosphazene chemistry. For over 20 years, the work of the Watertown labs, with the support of ARO, catalyzed not only the fundamental research exploring the synthesis and properties of this new class of inorganic polymers but also the development of polyphosphazenes and phosphazene fluids for the Army, other DoD and commercial applications.

Adhesive Bonding

Prior to 1986, research on adhesive bonding at Watertown consisted of a series of largely unrelated efforts aimed at the solution of specified problems.

All that began to change in the summer of 1985 when an Army Cobra helicopter experienced the in flight loss of a 10 foot section of the polyurethane rain erosion boot from the leading edge of one of its rotor blades. The resulting aerodynamic imbalance caused the near loss of the aircraft and those aboard. Subsequent investigation revealed that the erosion boot separated from the rotor blade because of a failure of the adhesive bond by which it was attached to the blade.

As a result of this near tragic incident, a Blue Ribbon Panel was assembled and charged with the investigation of

adhesive bonding problems in Army helicopters. AMC later broadened the Panel's investigation to include bonding problems in ALL materiel, from missiles to gas masks, from wheeled vehicles to fuze components.

The study's conclusions and recommendations became the basis for the Army's Adhesive Bonding Improvement Initiative. MTL was designated lead laboratory for the Program.

The investigatory panel had discovered that problems requiring immediate attention were not the result of a lack of knowledge as to how to produce the bonds. Rather, they arose from a failure to properly perform the bonding process in the factory. Therefore, it was recommended that a model approach to their analysis and correction be developed for each class of material and that this approach be widely applied across that class. Furthermore, to heighten awareness of adhesive bonding as a serious structural issue, training in the theory and practice of adhesive bonding was to be offered to all organizations within the Army whose supplies and equipment utilized adhesive bonding in their fabrication. This training was developed and presented by members of the Adhesives Branch at Picatinny Arsenal with the advice and assistance of Watertown personnel.

The approach to the solution of long term or potential problems in next generation and later systems was embodied in the recommendation that an Adhesive Bonding Research Plan of Action be developed and implemented. Formulated in 1986, the plan took strong note of the multidisciplinary nature of adhesion science, which involves chemistry, mechanics and surface science.

The plan was implemented as a major Program beginning in FY87. One program deals with the adhesive bonding of new materials which are emerging from the laboratory and are being considered for use in systems under development. In looking at classes of material the question of the adequacy of state-of-the-art bonding processes was addressed.

Elements of this program were conducted both in-house and at Imperial College, London. The in-house effort focused on the bonding of metal matrix composites. At Imperial College the bonding of thermoplastic matrix composites was undertaken. The overall conclusion is that, for the materials investigated, surface treatments are available which provide good quality bonds. The practical significance of the work is that adhesive bonding, with all of its attendant advantages, can be used for the fabrication of structures from these advanced materials.

The long-range objective of the basic research activities has been to contribute to the development of a global model of adhesive bonds sufficiently detailed and sophisticated that the entire life cycle of the bond from the initial design to the prediction of its in-service failure is possible. The Chemistry of Adhesives program is an element of that effort.

This program has looked closely at the nature of the interphase (the transition layer between the adhesive and the surface of the adherend) which arises when an epoxy adhesive is used to make a structural bond to aluminum. Using both model

adhesive components and high surface area adherend surface models, it was demonstrated that the molecular structure of the cured adhesive in the interphase region differed dramatically from that cured away from the surface. This gives rise to an interphase structure having mechanical and physicochemical properties which differ significantly from those in the bulk adhesive. Since it is in the interphase that load is transferred and most deterioration initiates, it is clearly critical that any predictive model be based on a good understanding of its structure. This program has contributed significantly to that understanding.

Because the interphase region is only about 100 to 1000Å° thick and is buried under many millimeters of conventional material, measurement of its properties is exceedingly difficult. Accordingly, an entire program addressing this problem was initiated in FY93. At this writing, only limited success has been achieved, and the work continues.

During the late 80s, Watertown established a major capability to perform molecular dynamics simulations or so-called molecular modeling. This ability to calculate and to visualize the motions of complex molecules in a wide range of environments was quickly appreciated as a powerful tool for the investigation of interphases. Study of the epoxy/aluminum interphase via molecular modeling clearly established the utility of the method for such investigations.

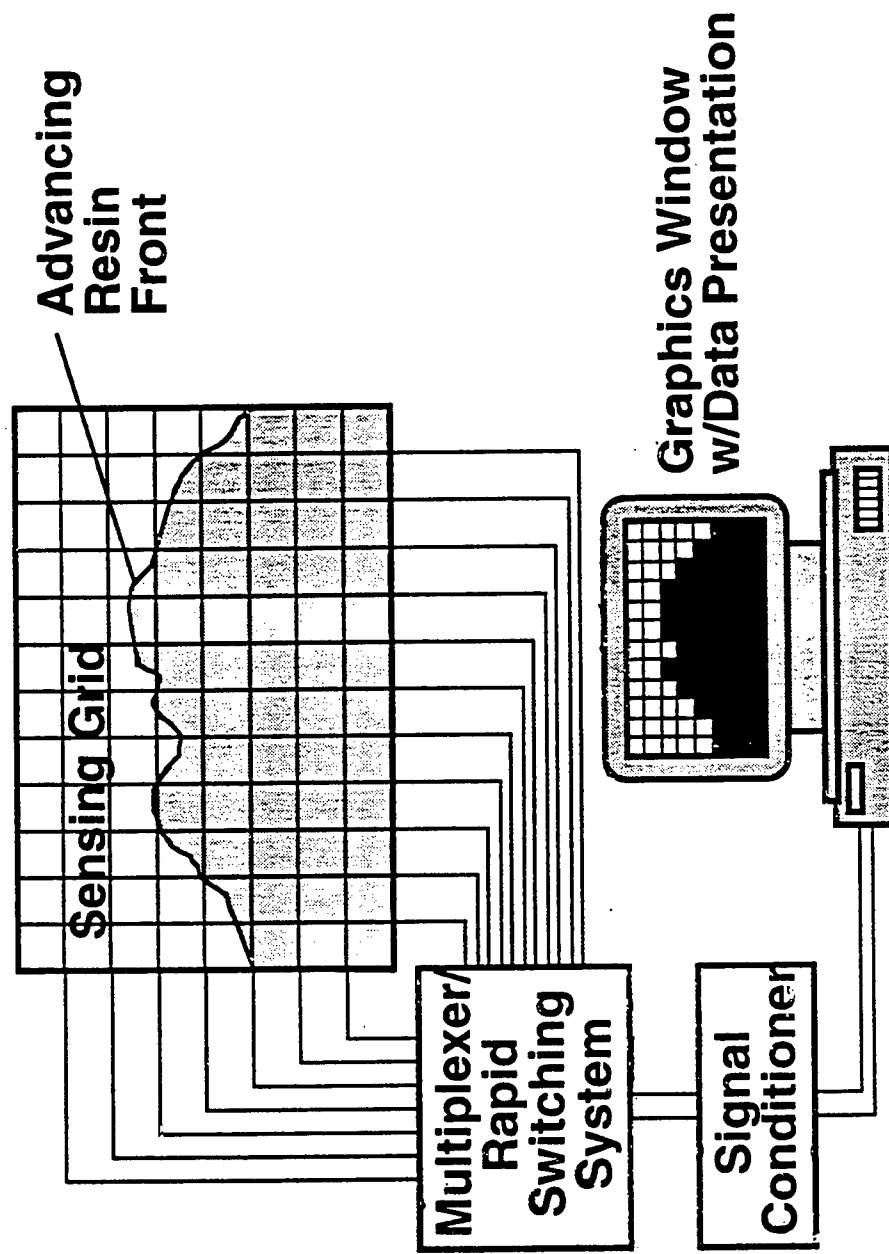
Taken together, these basic and applied research programs have contributed significantly to the advancement of adhesive bonding science and technology, especially in support of the application of adhesive bonding to the fabrication of Army materiel.

The SMARTweave System

Watertown has a long history of demonstrating the performance advantages of polymer-based, fiber reinforced composite materials in a variety of Army relevant applications. However, these performance advantages often carry cost structures that can limit their application. The Materials Directorate has taken the lead in identifying and integrating emerging technologies to impact the largest source of these costs: the manufacturing cycle.

There are a variety of manufacturing processes available for fabricating fiber reinforced polymer composites. The type of process can be broadly described in one of two ways. The first is the conventional "prepreg" approach wherein resin is applied to the reinforcement, partially cured to promote ease of handling, and then refrigerated until it is used to lay up a part. Prepreg parts may be processed in an autoclave, an oven, or heated press. The second class of composite processing is "wet" fabrication. In this case resin, typically under pressure,

THE SMART Weave SYSTEM



is allowed to impregnate the reinforcement and, with the application of heat, is cured in essentially one processing step. Typical examples of this process are filament winding, pultrusion, and resin transfer molding (RTM).

RTM is particularly attractive in that it is an effective technique for manufacturing low to moderate quantities of material; often RTM is used to prototype structures to demonstrate the advantage of composite materials. With an increasing emphasis on affordability, RTM is being examined as a serious alternative to more exotic, expensive and time consuming methods of composite production. However, enhancement of the RTM process itself is necessary if it is to compete in these higher performance arenas, and to that end manufacturing research activity in RTM has increased significantly over the last five years.

The goal of the present research is to directly impact RTM by identifying inherent problems in the process and developing a suite of software and hardware tools to resolve them. One example of this type of research is the SMARTweave program. SMARTweave is a relatively inexpensive, highly flexible, efficient system for acquiring polymer resin flow data during the impregnation phase of wet composite processes such as RTM. Specifically, SMART is an acronym that stands for "Sensors Mounted As Roving Threads." The principal philosophy used in the development of the SMARTweave system was to devise a means for deploying a multitude of low cost sensors easily so that one could visualize, in real time, the flow behavior of the resin in three dimensions.

The SMARTweave system can be deployed in three basic modes. First, it can be used as a diagnostic tool to aid manufacturing engineers and technicians associated with the impregnation phase to observe, and thereby correct, resin flow problems. Second, the SMARTweave data has the potential to serve as the primary feedback in an intelligent control system that can learn and compensate for errant resin flow fronts on line. Third, the same SMARTweave sensing array used for flow monitoring can be used to monitor the structural health and battle integrity of a fielded composite component.

SMARTweave started as a simple sketch on the back of a napkin and has since become one of the Top Five Programs in the Materials Directorate, with over \$400,000 in customer research support. In 1990 and 1991 it received internal support under the ILIR Program, which provided modest but essential funding necessary to prove out the philosophy of the SMARTweave approach. The successful pilot demonstration of the concept allowed for transition to one of the core programs in the Materials Directorate in 1992. It was chosen as an ARL Focus Program in 1994, and is currently cited as an Army Science and Technology Objective (STO) program. SMARTweave is a U.S. patented invention with 15 claims protecting both the method and apparatus aspects of the system. The patent was issued in May 1993 (U.S. Patent No. 5,410,299), and the Materials Directorate plans to license

the SMARTweave technology later this year.

The SMARTweave team has steadily grown to include a diverse group of disciplines, such as computer engineers, neural and cognitive scientists, plastics engineers and materials engineers. The SMARTweave program is an excellent example of the Federated Laboratory concept, wherein both academic and industrial resources have been leveraged in the development of the system. Furthermore, extensive inter-laboratory collaboration with ACIS (Advanced Computation and Information Sciences) has led to the integration of both virtual and experimental tools that could substantially impact not only Army composite production costs, but global competitiveness in the RTM arena generally.

Oxynitride Glasses and Fibers

The small amount of literature on oxynitride glasses that existed at the time (1980-81) this research started confirmed that nitrogen substitution could produce glasses with higher hardness, stiffness and strength than had ever been obtained for any oxide glass. Improved glasses were of interest to the Army for transparent armor and for improved glass fibers for lightweight composites. The first three years or so of the Watertown oxynitride glass research program were spent on the development of methods for making glass in sufficient quantities for the fabrication of specimens for testing. Later, emphasis shifted to the most significant outcome of this research, the invention of high modulus oxynitride glass fibers.

The glasses that were investigated in the program were of the general formula $M-Si-Al-O-N$ (where M is Ca, Li, Mg, or Y). Early emphasis was on yttrium-containing glasses, and techniques were developed for making glass batches of up to 100 grams or more. Glasses were prepared at AMMRC for in-house testing and evaluation as well as for collaborative programs. The latter included corrosion testing at Battelle Pacific Northwest Laboratories and the preparation of a large quantity of 100 g glass disks for Hugoniot impact testing at the Technion in Haifa, Israel. Spin-offs from Watertown work include the fabrication of large (100 mm diameter), transparent Y-Si-Al-O-N glass disks under contract at the Idaho National Engineering Laboratory, and an Army European Research Office contract on oxynitride glass matrix composites at the Technion. Further research was done on, and published on, glasses in which $M = Li$ and Mg . The research on bulk oxynitride glasses fulfilled the goal of demonstrating the fabrication of such glasses in quantity, and led to the measurement of the highest elastic modulus value ever reported for a glass, 185 GPa.

Work on oxynitride glass fibers, begun in 1984, led to the first patent ever issued on such fibers. That patent, U.S. 4,609,431, heavily influenced subsequent work at Shimadzu Corp. in Japan aimed at the commercialization of oxynitride glass

fibers. The fiber work also attracted interest from Owens Corning Fiberglass Corp. and PPG Industries, Inc., both of whom entered into cooperative R&D agreements with MTL. The glass receiving the most attention in this research was a Mg-Si-Al-O-N composition similar to commercial "S" glass, but with up to 4 atomic % nitrogen substituted for oxygen. The program demonstrated the feasibility of producing small diameter (10 mm or less) glass fibers with elastic moduli 30% higher than "S" glass at rates (1500m/min) close to commercial production rates. While the oxynitride glass fiber work attracted worldwide interest from many sources, oxynitride glass fibers are still not a commercial reality. Nevertheless, the technology developed at Watertown represents a milestone in this field, and the information generated on oxynitride glass programs represents a valuable resource for future development.

Ceramic Fracture Mechanism Maps

The drive to utilize advanced ceramics in structural applications prompted Watertown to conduct a great deal of mechanical property characterization, especially at high temperature. A variety of failure mechanisms were identified, including brittle fracture, slow crack growth (stress-corrosion cracking), and creep fracture. In many instances, several mechanisms of strength degradation could be operative simultaneously. The Ceramics Division of Watertown pioneered the routine usage of very long-duration stress rupture testing in ceramics, with as many as 25 flexural stress rupture test rigs that operated up to 20,000 hours at temperatures up to 1500°C. A simple, low cost test furnace was invented for this purpose and was widely adopted throughout the ceramic industry. Following ideas first proposed for metals at the University of Cambridge in England, hundreds of Watertown test results were integrated into fracture mechanism maps which enabled users and scientists to quickly assess the temperature and stress regimes where fracture of particular ceramic materials could occur and the mechanism by which it would occur. The fracture mechanism maps developed at Watertown helped overcome resistance to the utilization of ceramics in heat engine applications and became a benchmark against which all future high temperature testing programs were compared.

Grain Boundary Structures

Almost all metallic and most ceramic materials are made up of many very small crystals. These small crystals are called "grains," and the surfaces along which they touch and bond are

called "grain boundaries."* The properties of the material depend not only on the properties of the grains, but also on how they interact across the grain boundaries. Moreover, because grain boundaries are imperfections at which the regularity of the crystal structure is disturbed, they are higher-energy sites at which diffusion, nucleation of new phases, corrosion, crack propagation, and other phenomena occur more easily. Because of the important role grain boundaries play, materials scientists have been concerned with the nature and structure of grain boundaries since at least the 1920s.

Early models postulated amorphous boundaries at misorientations greater than approximately 20° , which implied isotropy within the boundary itself and no change in energy with misorientation across the boundary, or with the inclination of the boundary between the grains. In the early 1960s, the coincidence site lattice (CSL) model was introduced. This model postulated that at certain special misorientations between the grains, there is a superlattice of lattice sites common to both crystals (coincidence sites), and that grain boundaries which followed densely-packed planes in this CSL would have a low energy because they would have atoms at the boundary on sites common to the two grains.

Researchers at Watertown made major contributions to the development of modern theories of the structure of grain boundaries in the period from the late 1960s to the early 1980s. There was experimental work on the faceting of grain boundaries in the hexagonal-close-packed metals zinc and cadmium; theoretical models refining, extending, and generalizing the coincidence model for grain boundary structure; and the simulation, using computers, of the motion of atoms at grain boundaries at elevated temperatures.

Faceting means that a general surface breaks up into a series of flat, crystallographically-oriented surfaces of low energy. At Watertown the observation was made that grain boundaries in zinc were faceted after being grown slowly from the melt.** This evidence for low-energy boundaries in an hexagonal-close-packed metal was important. Nearly all previous evidence for low-energy boundaries were in cubic metals. Later it also was shown to occur in cadmium (another hexagonal metal). In addition, there was not just one special boundary, but a series of such boundaries in which the inclination of the facet changed systematically with misorientation.

Analysis of the crystallography of the grain boundary facets showed that an extension of the coincidence model was necessary to deal with non-cubic crystals and to explain the inclination/

* If the crystals are the same phase; otherwise, they are called "interphase boundaries."

** Faceting can also be due to kinetic factors during crystal growth. Long-time annealing experiments were carried out to eliminate this possibility.

misorientation relationship. There are important differences between cubic and non-cubic crystals. In both types of crystals, grain boundary dislocations (GBDs) are present to preserve low-energy patterns characteristic of exact coincidence site lattices (CSLs). In cubic crystals exact three dimensional CSLs can be found for rotations about any axis. This is not the case in non-cubic crystals, where in general only near, not exact, CSLs can occur in three dimensions. The presence of an additional set of GBDs in the boundary is necessary to compensate for the distortion implicit in near-coincidence. It was shown that it is this extra GBD array that caused the systematic change in inclination with misorientation. Not only was the model successful in explaining the crystallography of the facets, it was predictive as a good model should be. The original facets in zinc were seen in a misorientation range between 31° and 36.5° of tilt about a $\langle 10\bar{1}0 \rangle$ axis. An early version of the model correctly predicted facets and the inclination/misorientation relationship for a misorientation range of 49.5° to 55.2° . In the mid 1970s, this near coincidence model was the most general model for grain boundary structure available.

In the late 1970s, the grain boundary work turned to pioneering studies using molecular dynamics to simulate in a computer the detailed motions of atoms at a grain boundary, thus simulating the boundary at elevated temperatures. This made possible the observations of kinetic processes occurring at the grain boundary and the calculation of the thermodynamic properties associated with the boundary. A striking result was the intimate coupling between grain boundary migration and grain boundary sliding. With the computational power available in the 1980 time frame, it was not possible to have large numbers of atoms in the simulations. A large system was simulated by the use of periodic border conditions. This restricted the simulations to grain boundaries without any defects. In such a system, grain boundary migration was always accompanied by grain boundary sliding, showing the intimate coupling of the atomic motions in the two processes, and, more importantly, that defects are necessary for mobility at grain boundaries. These studies were some of the very first simulations of dynamic phenomena at grain boundaries. The impact of the work was such that an invitation was extended to include the work in a volume of Progress in Materials Science dedicated to the founding editor, Bruce Chalmers, upon his retirement.

Grain Boundary Cohesion

A microscopic, quantum-mechanical, investigation of the most intimate interatomic processes which make a material what it is, a pipe-dream of materials scientists only 20 years ago, is now approaching reality. During the past decade this has become possible due to the explosive progress in developing state-of-

the-art first principles methods of band structure and total energy calculations, as well as the advance of even faster supercomputers and efficient computational methods.

In 1988, at MTL, a 6.1 research project was started, directed at elucidating the energetics of impurities in grain boundaries (GBs) of iron-base alloys and tungsten, and analyzing the effect of these impurities on the intergranular cohesion at the electron-atom level.

The fundamental objective was a deeper understanding of the cohesion-decohesion processes at the microscopic level, laying a foundation for "smart design" of more ductile and tough alloys. Using the semi-empirical approach (the so-called modified Embedded Atom Method), as well as first-principles modeling (the Linear Muffin-Tin Orbital--LMTO--Method), significant progress in understanding mechanisms of intergranular cohesion was achieved, and important predictions have been made.

As has been known for decades, the reduced cohesion of GBs is often the controlling factor limiting ductility, and hence performance and reliability of high-strength metallic alloys. Intergranular embrittlement in metals is usually caused by impurities segregating towards the GBs. A ductile-brittle transition temperature as low as -196C was observed in high purity tungsten single crystals obtained by electron beam zone melting with special impurity gettering. Impurities present in parts per million (ppm) bulk concentrations can result in a dramatic decrease of plasticity, drastically degrading mechanical properties of metallic alloys, and thus posing significant technological and application problems.

This detrimental effect of minute impurity concentrations can now be readily understood. A simple estimate shows that one ppm amount of impurity is sufficient for saturating all the grain boundaries in a typical grain-size polycrystalline material. If a given impurity hampers the intergranular cohesion, this small amount would be very detrimental. Sensitivity of the ductile-brittle transition temperature to the grain size confirms the above physical concept: the larger the grain size, the smaller amount of impurity is needed to saturate the GB. Fine-grain polycrystals are known to be less brittle.

If impurities are the main cause of embrittlement, removing "the harmful" impurities, such as oxygen, nitrogen, phosphorous, sulphur, arsenic, antimony, etc., from the GBs is an obvious way of improving ductility.

This is conventionally done by gettering--alloying with another element that forms a thermodynamically stable phase with the harmful impurities. This process, however, requires careful control since the ductility upon gettering will be improved only so far as these second phase precipitates remain fine; any coarsening of precipitates, such as by so-called Ostwald ripening, would result in an adverse embrittling effect by another mechanism.

Another way is alloying the material with an element, which would increase solubility of undesirable impurities in the bulk, thus removing them from the GBs. This is probably the mechanism of the so-called "low-rhenium effect" in tungsten: alloying with 2-5% rhenium significantly improves tungsten's ductility.

However, as a direct result of our research, yet another novel way of cleansing GBs of impurities was suggested: the so-called "site-competition cleansing"--microalloying with an element, which, being more thermodynamically stable at GBs than an undesirable impurity, would displace the latter off the GB.

As follows from the analysis, in a clean GB, the main cohesive force bonding the adjacent grains together is between the nearest host atoms located across the GB. If an impurity atom is present in the GB, the distance between the host atom and the impurity is shorter than the host-host distance; this chain, host-impurity-host, plays the crucial role in the cohesion. Analysis of the electron-atom interactions in the GBs in iron and tungsten allowed important conclusions to be drawn on the nature of intergranular cohesion/decohesion in these metals.

It was found that in iron, in a typical GB environment, carbon and boron on the one hand, and hydrogen, oxygen, phosphorous and sulphur on the other hand, demonstrate a quite different behavior. Carbon and boron have a strong bonding with the iron atoms both in the GB plane and across the GB, while hydrogen, oxygen, phosphorous and sulphur, dramatically weaken the bonding across the GB, at the same time preserving a relatively strong cohesion in the GB plane.

Based on the analysis of the calculated relative energies of the impurities in the GB, it was deduced that the so-called "site-competition effect" would play an important role, affecting impurity distribution in GBs. Among the impurities analyzed, both in iron and tungsten GBs, boron has the lowest energy. Thus boron would tend to displace the other impurity atoms off the GB, thereby improving the resistance to brittle fracture.

Another important result is understanding the decohesion effect of hydrogen in iron. Contrary to a general belief, hydrogen does not contribute its electron to the iron d-bands at all. Instead, the electron stays very strongly localized around its proton. There is also virtually no hybridization with the iron electrons, and no effect on the iron atom magnetization. As a result, the interatomic bonding along the chains via hydrogen atoms is very inefficient, which results in significant weakening of the intergranular cohesion.

In tungsten, as in iron, boron also plays a dual role. Apart from being a "site-competition GB cleanser," boron enhances the intergranular cohesion, thus making brittle fracture more difficult.

Based on these findings, a new way of ductilizing tungsten was proposed. As follows from the theoretical predictions, microalloying tungsten with 10-50 atomic ppm of boron should result in significant ductilizing, thus lowering the ductile-brittle transition temperature.

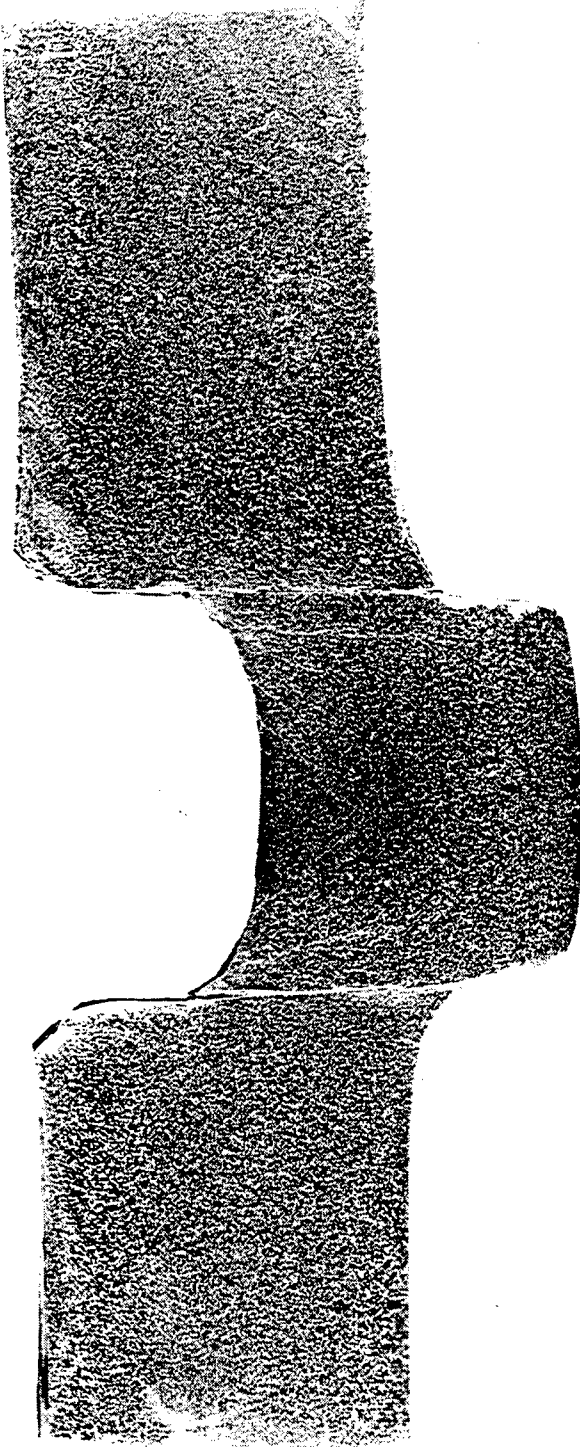
These results are also important for understanding the decohesion mechanisms responsible for embrittlement in iron and iron-base alloys, and should lead to improved steels for Army applications. As an active participant in the Steel Research Group (headed by Prof. Gregory Olson, now at Northwestern University, Evanston, IL), Watertown has strongly contributed to development of new and more advanced alloys.

Looking ahead, an important direction of research is the investigation, at the electron-atom level, of the effect of substitutional alloying with a "third element," which, by modifying the electronic structure, would neutralize the decohesive effect of the "harmful" impurities. Understanding the paradigm behind such an alloying, would make possible the creation of a "quantum steel" (the term coined by Dr. Olson).

This research, together with the independent calculations of Prof. Freeman's group at Northwestern University, will enable the building of a more quantitative foundation for the prediction of the impurity embrittling effects and the neutralization of them. Such understanding can be an important input into theory supported design of new embrittlement resistant high strength steels and heavy alloys, both for ballistic protection and KE penetrators.

Adiabatic Shear Deformation

A milestone in the study of adiabatic shear band development was published by C. Zener and J. Hollomon while working at WAL during the early 1940s. Experiments to determine the influence of strain-rate on the isothermal stress-strain curves of steel demonstrated that an increase in strain-rate has only a small mechanical effect (see Viscoplasticity and the Zener-Hollomon Parameter). However there is eventually a change in the deformation process from isothermal to adiabatic deformation. The dynamic consequences of adiabatic conditions were demonstrated by using a die and punch set-up to indent a thick steel plate. By dropping a weight on the punch, such that a 10 ft/sec impact velocity was produced, a strain-rate of $2 \times 10^3 \text{ sec}^{-1}$ was observed. The punch penetrated 1/8-inch into the plate, producing a 1.25×10^{-3} inch white shear band, indicating a shear strain of nearly 100. Their computation indicated that for these conditions a temperature rise of $1,000^\circ\text{C}$ would be expected for a shear strain of only 5. The white band in the adiabatic shear zone is a characteristic of steel that is rapidly quenched by the adjacent material of the steel plate. The occurrence of adiabatic shear band formation, a form of plastic shear instability, has been observed in ordnance applications such as the penetration of armor, deformation of penetrators, and the break-up or fragmentation of materials. Adiabatic shear band formation and resulting fracture is desirable in the design of



Failure of armor plate by plugging. The sides of the plug are bounded by adiabatic shear bands.

fragmentation applications and in the deformation of penetrators while the opposite is true for armor. The observation of adiabatic shear band formation also occurs in many non-ordnance applications, such as discontinuous chip formation during machining, dynamic shearing of plate and punching, as well as spalling of impacted hammer heads. The Zener and Hollomon study lay the foundation for subsequent world-wide research by their successors at AMMRC and elsewhere. The Watertown work will be described in the following paragraphs.

There is an inherent difficulty in making quantitative in-situ experimental observations of the initiation and propagation of adiabatic shear bands. This problem was partially overcome with the use of a semi-empirical relation, derived by G.B. Olson while at Watertown, for use in computer simulation of dynamic plastic deformation. The strain localization phenomenon of adiabatic shear is generally attributed to the plastic instability arising from a thermal softening effect during adiabatic or near adiabatic plastic deformation. High strain-rate adiabatic thin-wall torsion tests on high-strength rate-insensitive steels were used to describe a simple expression having the form of a polynomial-exponential function. With parameters obtained from torsion tests, this expression was successfully used in computer simulations for the development of intense shear band localization in a simply-loaded body. Strain localization was computed for both quasi-static and dynamic deformation conditions. Subsequent testing of double linear-shear type specimens, for both quasi-static and dynamic conditions, revealed that in addition to a thermal softening effect under dynamic conditions, there was also a softening effect due to the formation of microcracks. These microcracks were attributed to microstructural inhomogeneities acting as initiation sites for microvoids and microcracking during the onset of shear instability. It was concluded that if the microcrack formation contributed to shear localization, then the application of pressure on the shear plane should delay both the onset of shear localization and the formation of adiabatic shear bands. This pressure dependence on the shear plane was demonstrated with double linear-shear specimens tested under quasi-static test conditions. The computer simulations, combined with experiments performed to produce intense shear localization under both quasi-static and dynamic conditions, had important ramifications in the study of armor penetration. In those situations where the defeat of armor occurs primarily by adiabatic shear localization, delaying the onset of shear localization can be a primary means of improving armor performance.

While all the factors underlying the shear instability observed during adiabatic deformation of high-strength steels are not well understood, the use of empirical adiabatic flow relations derived from test results has allowed successful computer simulation of strain localization and an examination of the manner in which dynamic deformation can modify the

development of flow localization. Additional quasi-static shear experiments, incorporating a normal pressure on the shear plane, indicate that for high-strength steels there are pressure dependent effects that operate to delay the onset of shear localization. Therefore, an understanding of the role of microvoids and microcracks in high strain-rate deformation of steels is essential to an understanding of the adiabatic shear phenomenon. From the viewpoint of a metallurgist, this might be a desirable circumstance. Rather than heat capacity, temperature dependence of flow stress, and strain-hardening capacity as the only important variables, an essential role of these fracture-related processes would mean that aspects of microstructure more amenable to metallurgical influence and control could have a decisive influence on the strain localization process.

Additional shear tests were aimed at elucidating the fundamental mechanism of shear localization underlying both adiabatic shear localization and fracture processes. Included in this study was the effect of hydrostatic pressure and austenitizing temperature on the critical strain to localization. As expected it was demonstrated that strain localization is driven by microvoid softening controlled by nucleation at 100nm scale particles. These findings were based on the pressure dependence of the instability strain, enhanced resistance to shear stability with particle dissolution, and direct observation of microvoids at these particles in the deformed material. The direct correlation between crack extension force and shear instability strain demonstrated that both fracture toughness and shear localization are dependent on such microstructural features as size, type and distribution of second phase particles.

In addition to the thin wall torsion and double linear-shear specimens already considered, "hat shaped" specimens were also tested under both quasi-static and dynamic conditions. Hat shaped specimens were tested in a modified Hopkinson bar apparatus using mechanical stop rings which allowed the shear strain introduced to be controlled. After deformation, the shear bands were metallurgically examined at various stages of development under controlled dynamic loading conditions. Experiments in this case also indicate that strain localization is driven by a microvoid softening mechanism. The shear bands were found to be heavily deformed martensite. The extremely fine grain-size together with the additional carbon in solution (from dissolved carbides) significantly increased the hardness of the microstructure. With deliberate control of microvoid nucleating particle dispersion there is the potential for design of armor with enhanced resistance to shear localization and ballistic plugging. These results were consistent with earlier conclusions that thermal softening is not the only important softening mechanism at high strain-rates.

The relation between adiabatic shear instability and material properties in steel was also studied by nucleating shear bands in hollow thick-wall right circular cylinders which were explosively expanded in a "quick-stop" containment apparatus.

This type of high strain-rate experiment, often referred to as a "contained fragmenting round" technique, interrupts the formation of shear bands and produces populations of shear bands that are suitable for metallographic and fractographic study. Like the other studies, this work focused on obtaining a better understanding of the fundamental behavior of adiabatic shear formation so as to enhance armor and penetrator effectiveness.

Viscoplasticity and the Zener-Hollomon Parameter

The development of an understanding of the general deformation behavior of metals at elevated temperatures pushed forward in several significant ways at WAL during the later years of World War II. These advances are primarily connected with the persons of Clarence Zener and Cpt. J.H. Hollomon. In a series of papers published in the years 1944-1946 an understanding of the modern theory of the micromechanical behavior of metals emerges with its emphasis on the behavior of dislocations. The Army has always had an interest in understanding metal deformation, both from the general perspective of the manufacturing of weapons and structures and from the need for specific application of improved armor and systems to defeat armor.

The most well known result to come out of this time was the observation that the stress at a given strain depended upon strain rate and temperature only through the single parameter P which they defined as

$$P = (\dot{\epsilon} / f_0) e^{Q/RT}$$

where R is the universal gas constant, T is the absolute temperature, and $\dot{\epsilon}$ is the strain rate. This combination has been known in the literature as the "Zener-Hollomon parameter." It can be considered to be a temperature compensated strain rate. It has been used extensively to correlate experimental results.

The studies that led to the proposal of the Zener-Hollomon parameter were part of the ongoing search of that era to determine a universal equation of state for the plastic deformation of metals similar to that which had been developed for an ideal gas. The current understanding is that such an equation of state does not exist since more extensive experimentation has shown that the material's deformation depends not upon the current values of the stress, temperature and accumulated plastic strain but must rather include the history of the deformation. This is done using internal variables along with temperature and stress to define the internal state of the material. It is of interest to note that forty years after the work of Zener and Hollomon the Army laboratory at Watertown sponsored research at the Massachusetts Institute of Technology

which essentially disproved the equation of state approach and replaced it with the state variable theory.

An additional result developed by Zener and Hollomon during this period was the correlation of tensile and torsional tests by means of the concept of generalized stress and strain. Some of the initial experimental results showing an approximate equivalence between the tension stress strain curve and the torsion stress strain curve is verified if the logarithmic strain measure and true stress are used. Again, the Watertown laboratory was also involved many years later in the first experiments showing that there is an important second order effect when conducting finite twisting of reduced section tubular specimens. Experiments provided accurate measurement of the axial stress that develops during the forward finite twisting of metals.

Research in Shock Physics

Background

Active research in shock wave physics, at Watertown, began in 1970. This research program first supported AMMRC Hardened Materials Development Program efforts to characterize materials in terms of characteristics needed for nose tips, heat shields, substructures, i.e., the interceptor principal load carrying component, motor cases, and antenna windows to function satisfactorily under the extreme stress and temperature environment lasting a few microseconds. In 1987, the shock wave experimental and related high strain rate facilities began carrying out research applicable to armor-armament interactions.

Contribution During 1970-1987

- The investigation on porous tungsten, a representative material for its potential use in transpirationally cooled nose tips on missiles established the limits of the flight environment within which such a material nose tip could be expected to be cooled by circulating coolant through its pores effectively. The investigation also for the first time established a general experimental procedure to investigate the dynamics of pore closure in a porous material under a high dynamic stress environment.

- The research on lead fluoride established that AB_2 type compounds, attractive from the point of transparent electromagnetic window development, can withstand a high stress pulse of short duration without losing its desirable

electromagnetic properties because it does not transform to its high pressure phase even when shocked to 30,000 atmosphere's pressure, equal to seven times the static pressure of transformation. A refined analysis of the experimental data and other data on isostructural BaF_2 showed that: 1) shock induced transformations are not always fast, and 2) surface damage induced in lapping plays a significant role in the initiation of transformation under shock conditions.

These important points were demonstrated theoretically and validated experimentally. It implied that the electromagnetic transmissivity of materials like BaF_2 will be preserved even when short duration stress exceeds the pressure of transformation and will probably withstand repetitive stress pulses, confirming the Navy experience that a detector such as lead telluride deposited on undamaged BaF_2 is more reliable and reproducible than when deposited on a lapped surface of the material. Sluggishness of a phase transformation under shock loading has important bearing on the armor-armament interactions.

- The results of pioneering shock experiments performed at high temperatures in Sandia National Laboratory during 1969 showed a paradoxical effect, indicating that the shock process can diversely affect the thermodynamic behavior of two isostructural high melting temperature materials like tungsten and tantalum. A careful re-analysis of the shock wave data revealed instead that the experimental data indicated a substantial loss of shear strength in tungsten but not in tantalum, a finding with important technical significance, i.e., the rate of change in pressure with energy (the value of Gruneisen parameters) in tungsten need not be reduced under shock loading. This result was of considerable importance to people interested in weapons development involving chemistry as well as physics. Further, this analysis of pre-existing shock compression data on polycrystalline tungsten revealed for the first time that a metal can lose substantial amounts of shear strength, thus altering the prevailing scientific view that the deformation behaviors of metals invariably follow a simple elastic-plastic model. The validity of this finding was later confirmed by a new set of experiments performed on polycrystalline tungsten at Sandia National Laboratory and at MTL.

Subsequent research showed that this elastic-isotropic deformation also occurs in MAR-M200, a super-alloy consisting of two coherent phases. A satisfactory physical (theoretical) explanation for the loss of shear strength in metallic material or a two-phase alloy is still lacking.

- Investigations into the deformation of MAR-M200 (a nickel based superalloy), prompted by its potential use as a lightweight heat shield structural material, provided a rich amount of information till then undiscovered in any alloy. In brief, the results of these investigations showed that it may be possible to fabricate material which is resistant to spallation yet can deform like a material without substantial shear strength. It

may be thus possible to exploit the critical properties of the two coherent phases to systematically tailor and produce superalloys with the desired mechanical response under impact loading.

- Materials used to shield against ballistic, thermal, x-ray or laser impact may be subjected to a threat of successive sudden energy deposits, e.g., as the result of repeated impacts. Therefore, one of the basic problems in characterizing a material for field use is to understand the response of the material under successive impacts. If the impacts are widely spaced in time, then of course the experiments to determine the response of the material are easy to conduct. If, however, the time spans between impacts are small, then one must design shock experiments differently, to deal with this more difficult experimental problem. During 1985-1987, an experimental technique was developed at ARL-MD to measure the shock responses of materials under two successive impacts which occur in such a short span of time that they may be characterized as double impacts under uniaxial strain condition. This new method was successfully used to obtain the responses of PMMA to 1.3 GPa and of sapphire at 9.0 GPa, and more recently in titanium diboride and aluminum oxide under double impacts. In addition, these experiments, for the first time, allowed one to learn about the behavior of a commonly used piezoresistive gauge material (manganin) under double impacts and double releases.

- Composite materials are increasingly playing important roles in achieving desired technical performance in diverse systems and components, both in defense and public sectors. SiC/2014-T4 Al was the first composite investigated under shock wave loading at ARL-MD in support of the structure portion of the AMMRC Hardened Materials Development Program. The investigations on this composite dealt with elucidating:

- 1) shock deformation and spall threshold of SiC/2014-T4 Aluminum;
- 2) equation of state of SiC/2014-T4 Al to 4.5 GPa;
- 3) modeling of SiC/2014-T4 Al to predict its elastic constants and thermal expansion from the elastic constants and thermal expansion coefficients of SiC and 2014-T4 Al; and
- 4) modeling of specific heat.

- One of the problems that shock wave researchers face is the replication of experiments under identical conditions. This is generally achieved by performing more than one experiment under substantially identical conditions. However, since shock wave experiments are not only difficult to conduct, but also very time consuming, the concept of a multi-beam interferometer was conceived which would allow an experimenter to conduct and replicate a set of shock wave experiments in a single set up. This concept led to the construction of a four beam velocity interferometer for monitoring the motion of a material under shock wave propagation conditions at four locations in the material, i.e., as if performing four different experiments under identical test conditions. In addition, the other advantages of

this interferometer are:

- 1) Since it is a non-contact technique to determine shock response of a material it can be used at temperatures above and below room temperature;
- 2) It has no upper or lower limits of application and needs no calibration;
- 3) It can be used to determine the responses of the constituents of a composite material with a dimension of approximately 0.5 mm by monitoring the motions of each of the components of the composite as well as the aggregate of the components in a single shock wave experiment.

Further refinements to this device were done by using optical fibers for transporting the laser beam from the lasing source to targets, from targets to interferometer, and from interferometer output to the photo multipliers during 1992-1994. This, at present, is the only interferometer of its kind in the world.

Contribution During 1987-Present

- An exhaustive experimental study on an elastomer was conducted to predict its deformation behavior under the field condition in which the material is likely to be used. A few of the noteworthy results of this investigation are summarized below.

- 1) The compression under stress is rate dependent;
- 2) The persistence of large volume change with pressure could be due to onset of glass transition in an elastomer under shock loading;
- 3) Equivalence of release states from shock loaded state of an elastomer and the quasi-static adiabatic volumetric compression of an elastomer;
- 4) Modification of a small amplitude pulse as a result of attenuation of longitudinal elastic wave at various frequencies.

The results of this study on the elastomer have been incorporated in a code used in support of the Navy's Insensitive Munitions Advanced Development program.

- Characterization of thick composites presents a unique challenge to experimentalists because of the variability in the lay-up of pre-pregs at various desired orientations and the variability in the properties of pre-pregs due to minor variations in the process of their preparations. An experimental program on a graphite-epoxy composite of interest to ARDEC and BRL was initiated to determine the variation in the elastic properties of this anisotropic composite as a function of frequency of vibration, material variability, and the magnitude of strain. During the course of this program a new method of determining shear elastic constants of a material at few kHz was developed. The results of this program show that:

- 1) A set of careful experiments can be performed to

determine all the nine elastic constants of an orthotropic composite as a function of frequency by dynamic measurements and to predict the deformation of the composite loaded quasi-statically in any arbitrary direction;

2) The influence of material variability on the value of elastic constants can also be precisely determined;

3) These measurements for the first time provide all the necessary information required by theoreticians to validate their models for the determination of the elastic properties of an orthotropic composite.

• Shock wave studies have been and are being carried out on various ceramics to determine the extent of damage induced in them under single and repeated shock wave/impact loading and its effect on their compressive and tensile strengths. Influence of pores and the presence of glassy phase in ceramics on their deformation behavior under shock loading is being investigated. In addition, equations of state of a couple of ceramics have been determined from the measurements of ultrasonic wave velocities under high pressures carried out jointly with Benet Weapons Laboratory. These measurements are critical for developing a fundamental understanding of the deformation of these ceramics under shock loading and for developing material models for simulations of ballistic events. Ceramics which are of interest are titanium diboride, aluminum nitride, alumina, silicon carbide, single crystals of alumina and quartz, and soda lime glass.

Titanium diboride: 1) The observed elastic behavior of titanium diboride inferred from the measurements of shock wave and release wave velocities and impact stress is deceptive in the sense that a small generation of vacancies while not influencing its compressive behavior reduces the tensile strength of the titanium diboride significantly.

2) The spall strength of titanium diboride decreases as it is subjected to a larger shock stress and the spall strength vanishes at its Hugoniot Elastic Limit, i.e., 13 GPa.

3) The reported phase transformation in titanium diboride at 4.5 GPa by the Russian investigators in 1986 was wrong and that the observed cusp in titanium diboride at 4 to 6 GPa as reported by researchers at Sandia National Laboratory and at MTL was due to onset of accelerated rate of defect generation in the diboride. This was established by conducting a novel experiment where a specimen of titanium diboride was cycled through a pair of shock-release cycles before being subjected to tension. The results indicate that the spall strength of the diboride reduces drastically when it is initially subjected to a stress higher than 6 GPa. But such a reduction is not observed when the diboride is subjected to less than 6 GPa.

4) The shear strength of titanium diboride continues to increase with increasing impact stress to 60 GPa under single impact during its both elastic and inelastic deformation.

5) However, the compressive/shear strength of titanium diboride appears to undergo a no change under repeated shock loading when the amplitude of stress does not exceed its HEL. But when repeatedly shocked above its HEL, the compressive strength of the material during the second shock is enhanced like that of an elastic workhardening solid.

Some of the results of this study has been used by the researchers at ARL-WTD. The implication of these results for the shock compaction of a brittle ceramic powder is that in order to obtain a fully dense brittle ceramic through the use of shock wave technique it is necessary to pay very close attention to wave reverberations in the ceramic as well as its attenuation.

AD995 alumina: The stress limit of elastic deformation is 6.8 GPa. The shear strength of the alumina attains a maximum value of 2.7 GPa at 11 GPa and from then on it begins to decrease at higher stresses and ultimately vanishes around 31 GPa. The tensile strength of the alumina is impulse dependent rather than stress dependent, and the tensile strength is retained beyond its elastic limit, unlike in titanium diboride. The trend in the shear strength of the alumina with stress suggests that this material when impacted by a tungsten rod at an impact velocity of 1.5 km/s will have no shear resistance to penetration.

Aluminum Nitride: Inelastic deformations of pure and yttria doped aluminum nitride are not the same. While the former tends to suffer a loss of shear strength, the doped aluminum nitride deforms like a ductile material when shock loaded above their respective elastic limits. The lateral stress measurements carried out by the researchers at the University of Dayton on aluminum nitride are inconsistent with their shock wave measurements. In other words, their claim that aluminum nitride provided by Dow deforms in an elastic-plastic manner is not borne out by their experiments. A careful analysis of all the existing data on aluminum nitride indicate that the absorption of kinetic energy of a projectile by a material which transforms to a denser phase involving a large volume change may not take place even when the pressure generated due to impact exceeds the transition stress by a factor of two.

Soda lime glass: Propagation of a wave front which appears to degrade the compressive strength of glass is observed when the impact stress exceeds 4.5 GPa. The propagation of this wave front is not due to a second order phase transition but is postulated to be either related to generation of cracks or to change in the relative proportion of a and b species of SiO_2 molecules in the glass. The suggested postulate will govern the design of future experiments to be performed on the glass.

Glass reinforced polyester (GRP): The results obtained so far indicate that this material is transversely isotropic and deformation is strain rate dependent. These results are being utilized by ARL-WTD to simulate the vibration spectrum of a structure made of GRP.

Installation of the Compression-shear wave facility at ARL-MD at the APG site, the only such facility in DoD, will permit direct measurement of the effect of shock compression on the shear deformation of a material. In other words, this facility will completely determine the behavior of a material under dynamic/impact loading and thus provide vital information pertaining to constitutive relations of the material and the nature of shear induced damage evolution in a material or shear induced phase transformation of a material.

Summary

During slightly over the past one and one-half decades, shock wave research at Watertown has addressed a variety of problems exemplified by the following:

- 1) To determine the effect of shock waves on the change in the permeability of materials with connected porosity (porous tungsten);
- 2) To investigate the effect of kinetics of phase transformation on the performance of substrate materials (isostructural fluorides, barium fluoride, lead fluoride);
- 3) To investigate the loss of shear strength of condensed materials under compressive stress and its effect on their tensile strengths, i.e., spall strengths (polycrystalline tungsten, MAR-M200, a nickel based superalloy);
- 4) To investigate compressive, tensile, and piezoresistive response of materials under repeated impacts (titanium diboride, polycrystalline aluminum oxide, single crystal sapphire, polycrystalline copper, PMMA, Lucite, manganin, etc.);
- 5) To determine nature of deformation of materials under shock-re-shock (plasticized polyvinyl chloride, glass reinforced polyester composite);
- 6) To determine changes in optical properties like transparency and refractive index of optical materials under shock loading (single Crystals of sapphire, and soda lime glass);
- 7) To investigate the effect of shock induced damage on the deformation behavior of ceramics and the role of glassy phase in ceramics.

In addition, the existing shock wave experimental techniques have either been modified or new techniques have been developed and implemented to address the specific problems related to the AMMRC Hardened Materials Development Program and armor-armament interaction. The new techniques developed are:

- 1) To measure degradation in the strength of ceramic

materials through the measurement of spall threshold under shock-release-shock-tensile loading;

2) To measure the nature of deformation of solids under repeated shock-release cycle;

3) To measure tensile impedance of materials, and tensile wave velocity under shock loading and rarefaction wave interactions; and

4) Development of four-beam velocity interferometer for any reflecting surface.

The Mescall Zone

The development of armor and armor systems was one of the key functions of the Watertown laboratories. The development of armor materials involved extensive materials research, ballistic testing and mechanics support. Beginning in the mid 1970s the laboratory developed a capability to model the ballistic impact event of projectiles impinging upon armor packages of different materials and configurations. This was possible due to the development of hydrocodes capable of solving the equations of motion and material behavior in an impact environment. The development of these codes was carried out beginning in the 1960s at the Department of Energy National Laboratories. The "father" of the ballistic hydrocode, Mark Wilkins, developed such codes at Lawrence Livermore Laboratory in Livermore, California. The two dimensional, finite difference based, hydrocode, HEMP, was developed by Wilkins and used by John F. Mescall and coworkers at Watertown to investigate material effects in ballistic simulation.

One of the primary results to come out of these studies was in the area of confined ceramic resistance to penetration. For ceramic armor contained between a steel backing and a steel cover plate Mescall and coworkers showed that a region of high mean stress exists within one penetrator diameter in front of the penetrator. This stress was seen to be high enough to fracture the ceramic by compression, producing a constrained region of comminuted material. The penetration process is then controlled by the flow of this fragmented material. This region of high mean compressive stress has been named the "Mescall zone" after Mescall who first deduced its existence. This international recognition by workers in the field acknowledges the insights shown by Mr. Mescall and the utility of mechanics approaches in complementing the microscopic studies of material science.

Research at Watertown on Percolation Theory Applications to Materials

In 1971 a paper was published by researchers at AMMRC on

"Connectivity in graded two-phase structures," dealing with the hypothetical case of a two phase material containing both ceramic and metal particles, with the volume fraction of ceramic grading from 100 percent at the top surface, to zero, with pure metal at the other surface.

What was not mentioned in the paper was the application which led them to consider that hypothetical problem. This application had to do with the possible improvement in armor protection that could be achieved by a graded armor in which the front surface is composed completely of a strong ceramic, but in which the composition thereafter would gradually and continuously change from 100 percent ceramic to 100 percent metal.

The problem with the usual ceramic armor is that although the shock exerted by an incident projectile may not fracture the ceramic at the front surface, since ceramics can withstand large compressional stresses such as are generated at this surface, at the rear surface a large tensile stress is produced when the shock wave is reflected. Ceramics cannot, as a rule, withstand appreciable tensile stresses, and therefore they will fracture there. This would make it seem advantageous to have a metal at the rear surface since metals can withstand larger tensile stresses. However if one simply adds a second layer of armor consisting of metal, this would only transfer the reflection producing the tensile strain to the interface between the two layers, fracturing the ceramic at that interface. (Of course the situation is somewhat improved, since the remaining metal armor still affords some protection.)

With the idea of gradient armor one hoped to avoid the abrupt change in elastic properties causing the reflection at the interface by making the transition from ceramic to metal very gradual. The paper mentioned above described some preliminary results from simulation and analysis which showed that an abrupt change in elastic properties might still occur even when the gradient in composition was quite gradual. This happens because the purely random clustering of ceramic particles could lead to irregular ceramic-rich regions leading to the rear surface.

The quest to understand these results more fully led the AMMRC researchers to become actively involved in research into "percolation theory" which is a mathematical theory dealing with the statistical description of the geometry of connections between objects whose contact with each other is governed by probabilistic rules. For materials science it becomes a tool for the study of "phase connectivity," which is a measure of the degree to which particles of a given microstructural constituent or phase of a solid contact each other to form more extensive multiparticle clusters.

In the general theory of percolation there are many ways of specifying the rules of connection and the description of the objects, which may be of different kinds and shapes; the geometry may be in two, three or other dimensions, and there may be any number of different kinds of questions that one can ask about the nature of the geometry of the connections. One of the simplest

geometrical questions, and the one that names this theory "percolation" is, for the case that the objects can be identified with pores in an otherwise solid medium, are there continuous paths formed by the pores in contact with each other that would allow a fluid to percolate from one region in the solid medium to another region separated from the first by a large distance?

The roots of percolation theory may be traced to another materials science application, namely the description of gelation in polymers by Flory in 1941. He considered that it will depend upon the probability that the individual monomers will form a bond with each other, i.e., become connected. Gelation occurs when this probability increases to the point that enough monomers bond with each other to form a large unit, large enough to extend over the whole region of the solution.

The AMMRC researchers recognized the important contribution that percolation theory might make to an understanding of the many properties of materials which are crucially dependent upon the nature of random inhomogeneities in their internal structure. They saw the importance of carrying out simulation studies of phase connectivity and how it may affect materials properties such as electrical and thermal conductivity, resistance to wear, to chemical attack and to aspects of crack propagation. The research that was carried out was in the forefront of percolation research at the time. It demonstrated that percolation systems follow scaling relations as do systems undergoing phase transformations. Researchers with whom Watertown interacted included those at Kings College and at Boston University.

An area of research which is closely related to percolation theory is that of fractal geometry. This has also turned out to have many applications to materials studies, for example, to characterization of surface roughness, to porosity, to fracture and fracture surfaces. At the time the AMMRC percolation work was begun the application of fractal geometry to materials was still in its infancy; although the first of the many Materials Research Society Symposia dealing with fractals did not occur until 1984, the AMMRC group contributed a paper to the 1975 Journal of Physics which dealt with the "fractal dimension" associated with the spanning length of percolation clusters.

Crystallographic Texture

It has been known for many years that the properties of metals are anisotropic. That is, many properties vary with the direction of measurement. Among the important engineering properties that exhibit this characteristic are elastic modulus, strength and ductility. This anisotropy arises from three major causes: grain shape, multiphase distribution and crystal orientation. For the important engineering metals, the first two causes have been the subject of much research and development. This is because the most used metals have either a body centered

cubic (e.g., steel) or a face centered cubic (e.g., aluminum) structure. With the introduction of titanium and its alloys (hexagonal structure) the anisotropic nature of this crystal became evident. As the technology of titanium developed, great effort was placed on producing high purity. This was required to produce a product that had adequate ductility and toughness required for engineering applications, thereby reducing the anisotropic effects of inclusions. The required heat treatment of this high purity product also retained the crystal textures that were developed during mechanical working.

Investigations and analysis carried out from the late 1960s to 1978 at Watertown documented that many important engineering properties of titanium alloys are anisotropic, and that their behavior can be predicted by single-crystal theories. It was demonstrated that marked improvement in critical material characteristics such as fatigue, toughness, strength level, etc. could be had by control of a texture/specimen orientation. For example, Young's Modulus was found to range from 14.2×10^6 PSI to a maximum of 21.0×10^6 PSI. Information developed was the basis of the Department of Army Heavy Lift-Helicopter Project office evaluation of textured titanium for the Advanced Technology Rotary Wing Program in June 1973. Over thirty technical publications dealing with textured titanium were published, including the in depth review (76 pages) "Properties of Textured Titanium Alloys," published by the Metals and Ceramics Information Center (MCIC-74-20) which remains to this date a state-of-the-art text.

Beginning in the mid 1970s, a cooperative government/industry effort to utilize crystallographic preferred orientation technology developed under previous titanium programs to improve the ballistic penetrative resistance of steel armor was initiated. Under MTL technical leadership, interrelated research and development programs and Manufacturing Methods and Technology efforts were successfully completed. These programs transferred the technology from the laboratory to industry. Full scale production of textured steel armor was successfully accomplished. Two eighty ton heats were control rolled, quenched and tempered to develop a specific desired crystallographic preferred orientation, resulting in improved ballistic penetration resistant armor. A new military specification MIL-A-46193 (MR) for the novel textured steel armor was issued August 31, 1988.

STANDARDIZATION

STANDARDIZATION

The Watertown Arsenal Engineering Standardization Division (ESD) came into being in the early stages of World War II. As part of the Metallurgical Laboratory, the ESD was called upon to develop engineering standards required for the procurement, testing and evaluation of metallic materials used in such Army systems as: tanks, armored vehicles, artillery, gun tubes, breech rings, body armor, and a variety of other ordnance parts.

During World War II, the ESD worked very closely with other design, engineering and testing segments of the Arsenal, providing up-to-date weapons systems for the Army. It was during these years that specifications were prepared for cast armor materials for use in combat vehicles; for rolled homogeneous armor plate for use on combat vehicles and for proof testing of armor defeating ammunition; and for Hadfield manganese steel for body armor inserts.

In the early 50s, the Ordnance Materials Research Office (OMRO) relocated from Washington, D.C. to the Watertown Arsenal site. In the 1962 merger of OMRO and WAL to form AMRA, the OMRO Standardization Office took over the WAL Engineering Division. The combined office continued to carry out standardization efforts for the DoD during the Korean Conflict and the Vietnam War.

The ESD, even under several agency and organizational changes, continued to be a leader for the Army Materiel Command and the DoD in developing specifications and standards covering the latest state-of-the-art materials required for army weapons systems. For example, from the basic early armor plate and cast armor specifications, the ESD became involved in the development of standardization documents for: wrought high hardness steel armor plate; high strength, high quality, wrought steel armor plate; and aluminum armor plate for 2219, 5083, and 5456 aluminum alloys.

Later ESD became responsible for a series of composite armor specifications including: MIL-A-46103 which covers the procedure requirements for lightweight, ceramic-faced (aluminum-oxide, boron carbide and silicon carbide) composite armor used for foot-soldier body-armor and aircraft armor seats; MIL-A-46108 which is used for ballistic protection against small arms projectiles (typical applications include vision blocks for military fighting vehicles and windshields and windows for military aircraft, tactical vehicles and armored limousines); MIL-A-46166, covering material for lightweight reinforced plastic/composite armor used in Army applications such as the Apache, Black Hawk, and Cobra helicopters; and MIL-A-46197 covering laminate fiber-reinforced composites for armored vehicles.

Expanded Mission: In the mid-1960s, to ensure that the best material standardization program would be carried out during the

design, development and acquisition process, the DoD established the Defense Standardization and Specification Program (DSSP). The DSSP is concerned with products and technology, including: systems, subsystems, components, equipment, parts, materials, processes and testing technology. The Standardization Division responsibilities were expanded to include managerial responsibility for 5 Standardization Areas and 2 Federal Supply Classes (FSC's). The Metal Finishes and Finishing Processes and Procedures (MFFP) Area assignment was established in June 1964 as a result of a recognized need to provide single management responsibility and direction to a widely scattered group of finishing documents. This need was established when it was acknowledged that it would be necessary to standardize and document coding designations for finishing systems on engineering drawings. Also in 1964, assignee activity for Areas covering Thermal Joining (THJM), Metal Castings (MECA) and Forgings (FORG) were transferred from the Naval Ship Engineering Center to Watertown. In 1968 Federal Supply Classes 8030 (Preservative and Sealing Compounds) and 9640 (Iron and Steel, Primary and Semi-Finished Products) were assigned to the ESD. The Standardization Area Assignment for Nondestructive Testing and Inspection (NDTI) was established in 1973 in support of maintaining the Army Materiel Command Industrial Training Program in Nondestructive Inspection of Materials (available to and for the training of DoD QA personnel). AMMRC was selected to be the lead laboratory for materials testing technology (including NDT), because it had a competent staff uniquely qualified in NDT expertise.

As a result of these new areas, the ESD's technical responsibilities involved some 2,000 documents, covering specifications and standards. Documents covered a wide variety of materials such as ferrous and non-ferrous metals, plastics, composites, ceramics, rubber products, finishes and adhesives as well as materials-related processes and test methods. New specifications also were prepared and continue to be developed in support of advanced materials development for improved producibility and reliability in Army weapons systems.

Government Private Sector Cooperation: The ESD was the prime mover in initiating a cooperative program with the American Society for Testing Materials (ASTM) to develop and adopt non-Government standards for DoD use, thereby eliminating duplication of effort and overlapping of coverage for materials products. The need for this became obvious with the expansion of its mission. There was an on-going need to review, revise, and amend the many existing specifications under its purview as technology evolved, as well as to develop specifications for new materials, processes and test methods. This cooperative program began in earnest in 1971 when, at the urging of the ESD, several top level representatives of ASTM, Industry and Government came together to present their views on such a program. The private sector welcomed this opportunity to reduce duplication. As a result of

the cooperation, the program grew rapidly. Well over 5000 non-Government documents have been adopted for use by the DoD acquisition community, allowing the cancellation of hundreds of outdated Government standards at considerable savings to the Government.

The ESD members have not only worked on the comparison of hundreds of ASTM (and SAE-AMS) standards vs. Government documents, but also many have served as Main and Subcommittee Chairmen and Vice Chairmen of ASTM Committees where they have been able to direct these comparison studies, incorporating military requirements into existing Non-Government Standards (NGSs). Partly because of the high level interest created by ESD's efforts in this program, the Office of Management and Budget established a national standards policy in 1982 (Circular A 119) on federal participation in the development and use of voluntary standards. Also, there is a DoD publication 4120.20 on "Development and Use of non-Government Specifications and Standards."

ESD standardization efforts are attested to by the awards given to various ESD members. One member received the ASTM Award of Merit and was named a Fellow in the society in 1978. In the Nondestructive Testing field two of ESD's members received the ASTM Committee E-7 on Nondestructive Testing "Charles E. Briggs Award" for their efforts in the Government/Industry Cooperative Program. In 1987 an ESD chemist was recognized for outstanding performance in developing the Standardization Program Plan for Composites Technology.

Computerization: In the late 1970s and early 1980s, Watertown became the first DoD agency to computerize its specifications and standards by establishing a hierarchical database. A management information system was established for the storage, retrieval and analysis of salient specification data. Information and data from approximately 4500 materials and materials-related standardization documents within AMMRC's areas of interest were captured and entered into the Computerized Standardization Search System (CS³). The system allowed multiple personnel, through video terminals, to access the computer and to obtain information on test methods and requirements, reference documents, cross-reference data and interrelationships between groups of documents. The system proved to be a valuable tool for obtaining information for preparing reports and special studies. It was the forerunner of today's commercial Specifications and Standards packages available on CD ROM turnkey systems.

The DoD-assigned managerial responsibilities included several standardization programs and involved the development, establishment and maintenance of a comprehensive and integrated system of documentation in support of design, development, engineering, procurement, manufacturing, maintenance and supply management. In comparison to other DoD standardization offices,

the ESD was unique in that most of its 23 members had degrees in several engineering fields and in several scientific disciplines such as chemistry, physics, metallurgy and mathematics. This enabled the staff to integrate with, and to understand, the research and development programs being conducted in the laboratory.

Composites: With a number of DoD cooperative composite materials projects going on within the services, a new standardization area was developed for Composites Technology (CMPS). The Army Materiel Command assigned Lead Service Activity responsibility for this CMPS Area to MTL in 1985. Watertown was responsible for preparing and maintaining the DoD Standardization Program Plan for Composites Technology. The Plan established overall DoD objectives in the CMPS Area and served as the primary management tool for decision making at all levels within the DoD. One major objective of the plan was to promote the transition of composites technology to Defense, and ultimately, to a broad range of civil applications by managing and coordinating the Plan with other government laboratories, private industry and professional materials testing and standardization activities, such as the American Society for Testing Materials and the Society of Automotive Engineers. ESD's responsibilities in the Area of Composite Materials (CMPS) included management of over 150 standardization documents and preparation of over 25 of these, including those on composite armor mentioned earlier.

Composites Handbook: A unique and very important aspect of Watertown's composite materials standardization program was the development of the Composite Materials Military Handbook-17 (MIL HDBK-17). The Handbook was initiated as an Engineering Standardization Project to provide statistically-based characterization data on current and emerging fiber-reinforced composite materials with guidelines for the testing, analysis, presentation and utilization of data. Historically, the Handbook can be traced back to ANC Bulletin 17, "Plastics for Aircraft," dated July 23, 1943. Handbook revisions were published in 1955, 1959 and 1971.

The original scope of the Handbook was reinforced plastics for aerospace applications. However, as the demand for property data and the range of composite materials grew, the scope of the Handbook was broadened to include all polymer matrix composite materials and revised to accommodate additional non-aircraft, combat military vehicles and other applications. In 1988, Watertown issued MIL HDBK-17B "Polymer Matrix Composites, Volume I, Guidelines," which described procedures for generating and analyzing composite materials data. Additional volumes--Volume II, "Materials Property Data" and Volume III, "Utilization of Data"--were released during the period 1989-92. Keeping pace with the rapidly evolving technology and increasing demand for

composite materials data, all three volumes were again revised and updated in February 1994 as MIL HDBK-17-1B Guidelines, -2C Materials Properties and -3D Utilization of Data.

MIL HDBK-17 is today regarded as the primary, authoritative source of statistically-based composite materials characterization data, reflecting the best available data and technology for testing and analysis and including guidelines for data development and usage. The document is widely used by design engineers and for specification of materials by DoD, FAA and industry. The Handbook is somewhat unique in that industry suppliers and manufacturers of composite materials and components are intimately involved with DoD and other government engineers and designers in its development. The handbook development process has also been opened to foreign participation in order to tap into foreign expertise and to place the United States (and hence the DoD) into the most advantageous position internationally. Use of the Handbook saves manufacturers and their composite materials suppliers millions of dollars with the elimination of repeated testing of the same material. A "living" document, the Handbook continues to evolve and to improve because of the dedicated efforts of the MIL HDBK-17 Coordination and Working Groups which meet semi-annually to act upon proposed changes and additions.

Standardization of Properties Testing of Ceramics: MTL took a lead role in the establishment of refining and standardizing test methods for ceramics. Although test methods were in existence for traditional or electronic ceramics, these were not applicable to the emerging field of structural or armor grade ceramics. Refinements in processing and reliability analysis enabled ceramics to be used in load bearing applications, but the lack of quality test data was an impediment until standard methods became available in the mid to late 1980s. Watertown took a lead role in rectifying this, which culminated in the creation and adoption of MIL STD 1942 (MR), "Flexural Strength of High Performance Ceramics at Ambient Temperatures" in November, 1983. This standard test method rationalized the testing procedure of the most common method used to measure ceramic strength. It was the first standard created in the United States for modern ceramics and was adopted by the American Society of Testing and Materials (ASTM) and served as the basis for similar standards in Europe. Superior quality test results, essential for reliability analysis and design, were routinely achievable and considerable savings realized through the adoption of the standard specimen sizes. An equally important benefit of this work was that it brought an awareness of the merits of standardization to the ceramics community and paved the way for the establishment of a new ASTM Committee, C-28 Advanced Ceramics, in 1986.

Another highlight of the ceramics standardization work was the creation of the world's first ceramic fractographic standard practice: MIL HDBK 790, "Fractography and Characterization of

Fracture Origins in Advanced Structural Ceramics" in June, 1992. This practice enabled scientists and engineers to quickly and efficiently locate the fracture origin and diagnose the cause of failure in ceramics. It transformed what had been described as a "black art," performed only by specialists, into a common analysis procedure.

International standardization: The ESD has maintained membership in over 20 non-Government Standardization Bodies (NGSB) and held chairmanship of approximately 25% of these committees. It was also active in the international standardization arena with participation in ISO committees on metallic coatings, plastics and steel. Standardization personnel also participated in NATO standards development and the ABCA Quadripartite Working Group on proofing, inspection, and quality assurance.

Back in the 1980s, DoD teamed up with industry to form Equal Partnerships, and it was customary for each of the leading Industry Standards Groups to take a turn at sponsoring a Standardization Conference about every other year. In 1993 the ASME-sponsored conference honored an ESD member as one of the founding fathers of the DoD non-Government standards program, and it was noted that under his leadership, Watertown was one of the first DoD activities to adopt international standards.

Acquisition Reform and the Future: The current Engineering Standardization Office is now actively engaged in the DoD Acquisition Reform program and is a part of ARL-MD. It has continued to excel under this merger, having been presented the DoD banner award for excellence and having been chosen the recipient of the 1993 Outstanding Performance Award for its Defense Standardization Program. The Materials Standardization Office of ARL-MD was also recognized for its distinctive contributions in promoting more effective standardization within the Department of Defense.

Through the years the ESD has made numerous contributions to the Standardization community. Its engineering and scientific staff has actively participated in Standardization conferences, exhibitions and symposia, making presentations and writing papers and technical reports which have been published in scientific journals and Standardization magazines. The staff has always been dedicated to promoting Army Standardization by developing specifications and standards for unique materials and will continue in this role by carrying out the Blueprint for Change issued by the Under Secretary of Defense for Acquisition and Technology. It will also serve the Materials Directorate by providing it with a route for technology transition by entering into cooperative agreements with other government agencies, industry and academia.

TECHNOLOGY TRANSFER:
AT THE CROSSROADS OF INNOVATION

AN AGE OF MANAGEMENT INNOVATION

As noted in the Introduction, a research laboratory has existed at Watertown since the early 1800s. Noted for its excellence and many innovations, the laboratory, like the Watertown Arsenal--its parent organization--was directed and managed by Army officers. With the closure of the Watertown Arsenal in the late 1960s, and the combining of the remaining research facilities to form AMRA, the laboratory became its own entity with its own mission. Significant perhaps with this change was the fact that with only a few exceptions this began the succession of civilian managers who brought a new "business" perspective to Army research.

During the leadership of Dr. Alvin Gorum, Director from 1970 to 1976, an innovative view of relating materials research to critical Army problems was initiated. Called "Systematic Planning for the Integration of Defense Engineering and Research" (dubbed SPIDER Chart), it became a widespread technique at all levels of Defense Department management to show relevance. This was particularly important during this period of general skepticism regarding the value of in-house Defense research.

The emphasis on relevance had its impact on many on-going activities. One of the long established Watertown activities was the Sagamore Materials Research Conference. Initiated in 1954 and held until 1976 at a Syracuse University conference site in the New York Adirondack Mountains, this conference was designed to bring together basic researchers in a specific materials field to present their technical results and to exchange information. Among the "specific fields" were: strength limitations of metals, behavior of sheet materials, high temperature materials, deformation processing, fatigue, strengthening mechanisms of metals and ceramics, surfaces and interfaces, block and graft copolymers, ultra-fine grain metals and ceramics, materials characterization and ultra-high strength steel technology.

With the increased emphasis on research relevancy and management oversight, the annual Sagamore conference took on a greater role. Ultimately relocated (several times) to larger quarters, these conferences became critical meetings of both dedicated researchers presenting and exchanging information as well as managers determined to assess the current state-of-the-art for investment purposes. To this day the Sagamore Materials Research Conference stands as a guideline for basic materials research investment in the coming years. Panels of experts from the Army, other government agencies, industry and academe annually select a specific material or basic research area at the threshold of a breakthrough. Invited papers are presented by leading researchers to their peers and to managerial leaders who will collectively direct and finance future efforts. Published originally as reports distributed widely to the participants, the sponsors and other government, industry and university research centers, the proceedings became commercially available as hard-

cover books, published through Syracuse University Press from 1961 and by Plenum since 1975. A review of these many published proceedings will aptly attest to the value and influence of this Sagamore conference series. A list is shown in Appendix D.

The success of the highly renowned Sagamore conferences in providing guidance in the basic research arena, led to the institution of the Army Materials Technology Conferences. Structured in a similar manner, these conferences were directed at the more applied aspects of materials development. These proceedings are listed in Appendix F.

In the early 1970s, some Congressional criticism of the Army management of its "Manufacturing Technology" program was voiced. A significant portion of this overall program was materials related, and AMMRC was an active participant. AMMRC was conducting many projects in the "Manufacturing Methods and Technology" portion as well as having the lead in the Materials Testing Technology efforts. Recognizing both the technical expertise which was present and the organizational and managerial skills which SPIDER Chart experts brought to the table, AMMRC was asked by its parent Army Materiel Command (AMC) to assist in the overall management of this vital Army program.

The Manufacturing Technology program (ManTech) had been designed to develop and implement new and improved manufacturing processes, leading to both reduced production costs and more rapid production in times of national emergencies--overall building a stronger industrial base. After using the SPIDER Chart concept to analyze current efforts, it became clear that a closer industrial tie was needed. In cooperation with the U.S. Army Missile Command (MICOM), the first Army Manufacturing Technology Assessment Conference was held in 1972. Attracting senior managers from both industry and government, including the Deputy Secretary of Defense, this conference enabled industrial producers of critical missile components to match their manufacturing problems with available technologies. Where no match was made, Army investment was provided to solve the problem. Future examination of this ManTech program showed that due to the new management emphasis, the Defense Department's investment in the program yielded an average return on investment (ROI) of 8:1.

The widely acclaimed success of this first conference led AMMRC to develop a series of similar efforts. The Aviation Systems Command (AVSCOM), the Tank-Automotive Command (TACOM), and the Electronics Command (CECOM) all participated in one or more technology assessment conferences--with like results. Selected manufacturing areas, such as metal chip removal, were also included as part of this endeavor.

With funding in short supply and the need to ever increase productivity, the exchange of information became crucial. The annual DoD Manufacturing Technology Advisory Group Conference (MTAG) was hosted, in rotation, by the Army, Navy and Air Force with its purpose to coordinate projects within the services. Beginning in 1977, AMMRC was requested to provide the

coordination and conference management during the "Army host" years. Recognizing the need to involve industry--"the Producers"--the conference expanded from a small in-house (DoD only) meeting of less than 200 attendees to an annual conference of 800-1000 with over 40% industrial participation--exchanging both technical data and policy information. By the early 1980s AMMRC had again taken the initiative and incorporated exhibits into the conference to display to both military and civilian leaders alike the results of successful taxpayer investment.

With the ever increasing amount of new technological information being generated, it became evident that easy access was critical, especially for small business and subcontractors. DoD had established several materials information analysis centers for this purpose which were being managed by AMMRC (at the request of DoD). Because of the growing importance of manufacturing technology, it seemed appropriate that a separate one-source information center for manufacturing technology also be established. After a detailed study was conducted under AMMRC sponsorship, the DoD agreed to provide the necessary funding, and the DoD Manufacturing Technology Information Analysis Center became a reality, a single source for all industry to obtain the benefits of new manufacturing technology development.

As an interim measure, the results of Army manufacturing technology successes were published through the U.S. Army ManTech Journal. This journal, edited by senior AMMRC managers, was published in the early to mid 1970s. Its importance as an information mechanism may be assumed by noting that the two largest subscribers were the USSR Embassy and a Hong Kong company. Obviously, only public information was printed.

In looking back at "SPIDER" charts; the Sagamore and Army Technology Conference series; the ManTech Assessment Conferences; and the overall Manufacturing Technology program, it is fair to say that the decades of the 1970s and 1980s were an age of management innovation in Army materials research and development. The expertise developed in conference management alone became evident when in 1992 the staff at MTL was asked by the Department of Army and AMC staff members to coordinate the first "open" Army Science Conference--another success in a long chain of management efforts.

One last episode in the list of Watertown's technical management achievements began in 1990. The end of the Cold War and the resulting downsizing of DoD staff and R&D budgets brought on yet another demand for management innovation to ensure the continuing technological superiority of U.S. forces. Up until 1990, the Defense R&D program was conducted more or less independently by the three services and by the Ballistic Missile Defense Office, the Defense Nuclear Agency and the Advanced Research Project Agency. Attempts to control overlap and duplication of programs consisted mainly of annual DoD reviews and of informal communications between bench scientists. There were, however, no formal attempts to plan complementary programs, to control redundancy, or to eliminate unnecessary and

duplicative facilities among the three services' laboratory structure. This lack of coordination among the services ended with the implementation of Project Reliance.

Mandated by Presidential directive, Project Reliance was a tri-service planning process administered through the Joint Directors of Laboratories, a General Officer command organization reporting to the Joint Logistics Commanders. Starting in 1990, technical panels comprised of representatives of all defense research entities were formed to focus on specific technology areas. The Technical Panel for Advanced Materials (TPAM) was one such panel. Its responsibility was to inventory existing programs and facilities, identify opportunities for consolidation, elimination and coordination, and from there proceed with the development of a truly joint service plan for all materials programs to be conducted under DoD auspices.

Several members of the Watertown technical and managerial staff were deeply involved in these planning efforts undertaken by TPAM. Indeed, the leadership of TPAM during its first two critical years was provided by the Watertown Technical Director, during which time important strategic policies and practices were formulated for the implementation of Reliance principles by the three defense materials communities. It was under Army leadership provided by Watertown, that the first two annual Joint Service Program Plans for Advanced Materials were assembled, which in FY94 presented a fully coordinated, and in many instances fully integrated, tri-service materials program in excess of \$200 million.

MANUFACTURING TECHNOLOGY (MANTECH)/MANUFACTURING SCIENCE AND TECHNOLOGY (MS&T)

The DoD Manufacturing Technology (MANTECH) program was formally created in 1969, having as its objective the advancement of the state-of-the-art in manufacturing through the establishment and demonstration of new technologies. MANTECH was designed to "bridge the gap" between research and development innovations and full scale production applications of new, more efficient technologies. Such technologies might involve processes and/or equipment advances. Earlier, however, in 1963 two separate functional areas of MANTECH had already been identified by the Army and funded out of the Army Materiel Command's Production Engineering Measures (PEM) line: Materials Testing Technology (MTT) and Manufacturing Methods and Technology (MM&T).

Watertown was instrumental in originating the MTT program when it repeatedly raised concerns that many testing ideas, proven feasible in R&D investigations, were not being advanced to the point where they could be used in actual inspection of manufactured components. It was finally successful in gaining AMC funding for MTT in 1963 and has managed the program ever

since. Watertown's efforts under the MM&T functional area also began in 1963 with programs on investment casting and centrifugal casting. After 1969, most of the MANTECH projects conducted under Watertown management fell within MM&T. Through the years Watertown has both managed and conducted in-house numerous MANTECH projects.

In 1975 the MANTECH Management Support Office was formed at AMMRC, which served as the technical support arm for AMC Headquarters on the MANTECH program. AMMRC shared dual responsibility with the Industrial Base Engineering Activity (IBEA) at Rock Island, Illinois for technical support to AMC Headquarters on MANTECH activities. It was a very significant activity and was organized at Watertown because of the recognition of AMMRC as a leading institution for manufacturing technology expertise in the Army.

In 1990 the Army MANTECH program was reorganized into Thrust Areas (with Thrust Area managers) as opposed to the traditional commodity command organization. Eleven Thrust Areas were approved and funded with Watertown designated the thrust manager for the Nondestructive Evaluation, and Composites/Adhesive Bonding Thrust Areas. In 1993 Watertown was named Thrust Manager for the Advanced Integrated Manufacturing Systems (AIMS) Thrust Area, and the Nondestructive Evaluation Thrust Area was reorganized into the Sensors in Manufacturing Thrust Area (still with Watertown as Thrust Manager). In 1994 the Metals Thrust Area was established with Watertown designated as Vice-Thrust Manager.

In 1993 the MANTECH program was recast into the present DoD Manufacturing Science & Technology (MS&T) program and organized as a Joint Directors of Laboratories (JDL) Project Reliance effort (MS&T Panel). The Army MS&T Program was organized around the five MS&T JDL Technical Sub-Panels (Manufacturing Systems, Electronics Processing and Manufacturing; Composites Processing and Fabrication; Metals Processing and Manufacturing, and Integrated Industrial Base Pilots) to parallel the DoD MS&T Reliance Panel structure.

Over the years, the Materials Laboratories at Watertown have made many significant contributions to manufacturing technology and the science of manufacturing. A few examples are described below (the responsible Army agency is shown in parentheses):

- Mobile Neutron Radiography System (Watertown)--The prototype for the first commercial mobile neutron radiography inspection device was constructed under the technical direction of Watertown engineers. A semi-mobile accelerator based neutron radiography system was constructed and successfully demonstrated. Capabilities were demonstrated on an aircraft for system positioning, real time image, wing flaw detection and corrosion detection.

- Computerized Color Matching of Textiles (Soldier Systems Command)--An objective computer-based textile color measurement and evaluation system was successfully developed and is finishing final demonstration trials at the Defense Personnel Support

Center. The spectrophotometer based system has a fail-safe calibration procedure to ensure system-wide accuracy. Benefits include fewer contractual disputes, improved quality of textiles used in military end items, and shorter turnaround time for pass/fail decisions to contractor.

- Automatic Inspection Device for Explosive Charge in Shell (AIDECS) (ARDEC)--Establishing a novel automatic inspection technology for explosives in shells after melt loading. The system employed filmless flaw detection techniques to provide automatic acceptance decisions at production speeds of 44 shells per minute. Computer data analysis permits a 100% shell sampling rate without the need for human X-ray film interpreters.

- Cryogenic Cooler Helium Leak Rate Test Set (CECOM/NVL)--Developed helium leak testing of castings for night vision Forward Looking Infrared System (FLIR) devices to eliminate those with porosity which can degrade the systems during use. As the castings were in the common module cooler stage, excessive helium leakage could cause inadequate cooling of the infrared imaging device, thereby producing improper functioning of the devices.

- Expert System for Test Program Set Quality Assurance (ESQA) (ARDEC)--Developed procedures to automate the repetitive and time-consuming task required to thoroughly analyze a Test Program Set (TPS) for quality and accuracy prior to acceptance. The new system will allow high quality TPSs that accurately and rapidly detect and isolate failures. ESQA is now a Tri-Service program which is expected to save hundreds of millions of dollars through DoD in the next ten years.

- Mobility Monitoring System (TECOM)--Developed a set of high performance, rugged data recorders for monitoring vehicle performance. Data compression algorithms were generated to provide up to a 1000 to 1 reduction in stored data values, allowing long-duration, high sample rate testing. The system connects both measured (temperature, vibration) and control (driver name, test course) type data. It can be used to test a variety of wheeled and tracked vehicles.

- Dynamic Indexing Station (Watervliet Arsenal)--Developed and implemented a dynamic indexing process for 105mm and 120mm cannon tubes which automates cannon straightness measurement and data acquisition, decreases the time and cost of inspection, and improves data integrity.

- Generic Shock Absorber Test Stand (GSATS) (Watertown)--Developed and implemented a diagnostic testing system that tests and classifies shock absorbers for combat and tactical vehicles using neural networks and a hydraulic test stand.

- State-of-Charge Meter for Non-Rechargeable Lithium Batteries (ARL/Electronics and Power Sources Directorate (EPSD))--Developed and implemented a state-of-charge meter for soldiers in the field to know whether a battery is good or bad. Use of the meter is expected to save millions of dollars in logistics costs.

- Production Test of Ultra-Safe High-Rate Lithium Manganese Dioxide Batteries (ARL/EPSD)--Developed nondestructive, in-process inspection and test procedures and devices for the

lithium manganese dioxide pouch cell battery technology. Enable the production of dual-use ultra-safe, high performance, cost-effective batteries for the Army.

- Automation of Roadwheel Endurance Test (Red River Army Depot (RRAD))--Developed automated temperature and endurance test equipment to test track vehicle roadwheel endurance and reliability. System was designed, constructed and installed at RRAD.

- Magnetic Flux Leakage Inspection System (ARDEC)--Developed an inspection system to automatically and nondestructively detect defects within the steel body of 40mm cartridges on the inside or outside diameter, or within the walls of all projectile surfaces, without regard to orientation of the item under test. Savings of more than \$20,000,000 has been realized in the screening of the cartridges from a suspended stockpile of seven million rounds of ammunition. Additional savings of \$50,000,000 will be realized.

- Introduction of ultrasonic cleanliness rating methods and standards for gun tube steel billets (Watertown). This became an industry standard for all steel.

The ARL Materials Directorate will continue to play a very significant role in the Army MS&T Program after it transitions to the Chestnut Run, Delaware and Aberdeen Proving Ground, Maryland locations. MS&T activities will be continued in: 1) project performance; 2) Thrust Area Management for Composites, Metals, SIM, AIMS, and MTT; and 3) technical support for the AMC Headquarters MS&T Office.

THE HISTORY OF THE MATERIALS TECHNOLOGY SCHOOL

The initial course to be taught at the Materials Technology School--originally called The Ordnance School--was introduced at 0800 hours on Monday, January 29, 1940, by the School Officer, Major S.B. Ritchie. The course, entitled "Metallurgical Processes and Methods of Analysis," was to end seventeen weeks later on Friday, May 24. The four months duration was necessary to complete all of the instruction, examinations and students' theses. The student body consisted entirely of U.S. Army officers--one captain and twenty lieutenants. The classroom was located in Building 152, just east of Watertown Arsenal's Main Gate; however, instruction in Theory of Interior Ballistics, Advanced Physical Metallurgy and Electrical Engineering and Laboratory was scheduled for Monday, Wednesday and Friday mornings at Massachusetts Institute of Technology (MIT).

In addition to the subjects being taught at MIT, a staff of fifteen instructors (including Dr. Horace Hardy Lester who established this nation's first industrial radiographic laboratory at the Watertown Arsenal in 1922) presented material on the following topics:

Erosion	Problem in Laboratory Procedure	Report Writing
Welding	Metallurgical Chemical Analysis	Pattern Making
Corrosion	Gun Steels and Armor Plate	Heat Treatment
Smith Shop	Engineering Data Analysis	Testing Materials
Radiography	Foundry Molding Practice	Centrifugal Casting
Cold Working	Laboratory Management	Arsenal Procurement
Macroetching	Spectroscopic Analysis	

Dr. Lester's work in industrial radiography throughout the 1920s and 1930s led to its unprecedented acceptance by the steel foundry and manufacturing industries as a valid and valued nondestructive testing (NDT) method (see Industrial Radiography in the Early Years section). This in turn led to the requirement for training ordnance inspection personnel in its application. Since Watertown Arsenal was the only installation possessing the necessary skilled personnel and the essential facilities, it undertook the task of filling the training needs for the Ordnance Corps.

With the development of other methods of NDT and their applications to the inspection of ordnance material, as well as their use by ordnance contractors as in-process inspection methods, the same procedure as that for radiography was followed. Watertown Arsenal became the authoritative source of knowledge in the Ordnance Corps for NDT, culminating in the establishment at Watertown Arsenal Laboratories of a Nondestructive Testing Center.

In June 1940, an Inspection School was organized at the Arsenal offering a six-week training course for inspectors. In January 1941, a ten-week advanced course was added. Portions of this course were held at Wentworth Institute and MIT. The course offered instruction in inspection procedure, gages, welding, radiography, magnetic testing, chemistry, physical testing, macroetching, general metallurgy and blueprint reading. Due to increased activities during World War II, the school expanded its program to offer training for supervisors, foremen, inspectors, and other departments. When many of the Arsenal personnel enlisted in the armed services, an intensive training program for men and women was instituted to meet the growing demand for operators of all types of machines.

Although the school trained inspection personnel throughout the Ordnance Corps, it was funded locally until 1957 when it was accepted as a formal industrial training program and centrally funded. By 1965, the school was offering only six different courses, covering Metals Inspection, Magnetic Particle and Liquid Penetrant Inspection, Radiography, Weld Inspection, Ultrasonic Inspection and Impact Testing. The instructors were selected from the laboratories based upon their fields of expertise.

When Watertown Arsenal closed in 1967, AMRA remained in operation only to become AMMRC one year later. At this time the training program was transferred to its final Watertown location in Building 313C. There the school continued to fulfill the

recurring need within the Army for the training, qualification and certification of NDT personnel. Training and certification of NDT inspection personnel within the Army has been required for many years by a variety of military standards and specifications: MIL-Q-45970, MIL-STD-453, MIL-STD-271, and so on, which are referenced in Depot Maintenance Work Requirements (DMWR's), Storage and Serviceability Standards (SSS's), Standard Operating Procedures (SOP's), work orders, etc. In order to introduce an organized approach to satisfying the requirements for NDT training and certification, DARCOM Headquarters published a regulation, DRCR 702-22, in October 1976, which established a uniform set of training and experience criteria, satisfying the minimum requirements of all commonly used military and commercial NDT documents. Furthermore, the regulation assigned specific responsibilities to DARCOM elements in order to achieve implementation of this program. The Nondestructive Testing School at AMMRC was assigned the responsibility for administering the NDT training and certification program within DARCOM. Accordingly, the courses offered were developed to maximize their application toward fulfilling job certification requirements.

In the late 1970s and early 1980s, many of the courses presented were being conducted by private companies under contract to the school. In 1981, a turnaround to this trend occurred when an innovative developmental program was instituted whereby professional educators would be hired with the plan to teach them NDT and then have them conduct the courses. Over the next three years, five such instructors were hired. They gradually absorbed the contractors' courses and provided training which was more in line with the needs of the Army. Level I and II core courses, with subsequent certification examinations for students who qualified, were established for the following methods: Radiography (RT), Ultrasonics (UT), Magnetic Particle (MT), Liquid Penetrant (PT), and Eddy Current (ET). Additionally, peripheral NDT courses were added to augment the core courses: Introduction to Nondestructive Inspection of Materials, Radiographic Film Interpretation, Ultrasonic Testing of Welds, Radiographic Testing for Quality Assurance Specialists, Nondestructive Testing for Product Quality Assurance, Weld Inspection, and Nondestructive Inspection of Welds. Thereafter, several Engineers were hired to provide technical expertise and balance to the staff and to develop non-NDT courses.

In 1985, AMMRC became the Materials Technology Laboratory (MTL). In 1986, the school's name was changed to the Materials Technology School, reflecting the expansion made to the variety of courses developed and taught by the Engineers: Basic Metallurgy, Introduction to the Practical Aspects of Corrosion and Deterioration Prevention and Control, Corrosion and Material Deterioration Prevention and Control in Aviation Systems, Corrosion Prevention and Control in New Systems Design, and Introduction to the Science of Corrosion. By this time the instructor staff had increased to 10 (most of whom were to earn from one to five ASNT Level III certifications), and over 1200

students per year were being taught the theory and application of corrosion prevention and control and NDT. As a cost-reducing effort to the Army as a whole, more than one-third of the students were instructed at their own installations, including locations in Germany, Wales, Korea and Japan.

During periods when instructors were not teaching, they were variously called upon to assist the Depot Systems Command in their Quality Systems Reviews, assessing the equipment, personnel, and programs relative to NDT; to provide similar services to private Army contractors; to develop/approve NDT inspection procedures at AMC (Army Materiel Command) sites; to perform NDT inspections; and to participate in or spearhead projects related to NDT and corrosion. The Materials Technology School had also become the point of contact at this installation for Failure Analysis and was loaning equipment and standards to Army installations with a short-term need. Equipment which would provide the students with state-of-the-art hands-on experience while at Watertown was purchased for the school. A self-contained microfocal X-ray machine, a real-time fluoroscopic X-ray machine and a computerized Ultrasonic immersion system were among the additions.

In 1987, it was decided that, as a cost-saving measure, the school would revert to a contractor operation, and central funding was reduced. When exorbitant contractor costs resulted in the rehiring of MTL instructors, courses continued to be of exceptional quality, but their number and sizes were greatly reduced.

With the 1990s came the concept of the consolidated lab, and the research missions at MTL became part of the Army Research Laboratory's Materials Directorate. When the Army Research Laboratory--Materials Directorate was slated for transfer to the Aberdeen Proving Grounds the Materials Technology School received no transfer offer and was informed that it would go out of existence. In the fall of 1994, the Combat Systems Test Activity at APG stepped forward with an offer to become the new administrators of the NDT Training and Certification Program. Appropriate approval was received at Aberdeen, and in March 1995, the school's equipment and course materials were transferred to their new home.

SMALL BUSINESS INNOVATION RESEARCH PROGRAM

One area of recognized accomplishment and tremendous spin-off in which the Army laboratories at Watertown have played a key role since program inception has been that of the SBIR program. From its creation by Congress in 1982 to the present, the Small Business Innovation Research program has had as its mission the fostering of new product and process development by small companies in defense-related scientific and engineering areas. Historically, small businesses have been one of the country's

principal sources of significant innovations. However, federally funded research and development typically occurred under the auspices of large businesses, universities and federal laboratories. Congress sought to remedy this disjuncture through enactment of the Small Business Development Act of 1982 (Public Law 97-219), under which the SBIR program was established. Large federal agencies with contract R&D budgets would set aside 1.25% of these allocated monies for small businesses. The eleven federal agencies which participate in the program set aside more than \$400 million a year in SBIR funding. The premise was that job expansion and economic growth would result from the greater use of small businesses in federal R&D. In addition to encouraging the utilization of small businesses to meet federal R&D needs, the program was given the following mandates: to spur technological innovation; to increase the number of federal R&D innovations achieving commercialization in the private sector; and to raise participation levels of minority and disadvantaged persons in technological innovation by granting awards to minority and disadvantaged firms.

The SBIR program consists of three phases. Phase I, the smaller research effort, demonstrates concept feasibility. This phase is initiated when a small firm submits a proposal in response to a government agency SBIR solicitation. The major R&D thrust takes place in Phase II and is expected to result in a well-defined, deliverable product or process. Program regulations require that these monies only be used in the first two phases of the program. In the third and final phase, commercialization and marketing are undertaken, with the assistance of nonfederal capital. The SBIR-developed product or process is now government procurable.

By far, the largest participating federal agency has been the DoD, whose umbrella encompasses involvement by the United States Army. MTL sponsored the first U.S. Army-wide SBIR contractor to reach and successfully complete Phase III, the U.S. Composites Corporation of Troy, New York.

While managing only 4% of the U.S. Army's SBIR program in terms of topics and funding, MTL sponsored 19% of the firms that were cited for their achievements in an Army Phase III report issued in mid-1990. Illustrative of Phase III successes occurring under Watertown backing are the following companies and accomplishments:

Prior to U.S. Composites being awarded an SBIR contract in 1984 as a Watertown-sponsored participant, the use of textile braiding with composites had been limited because no viable means existed for applying resin to fibers moving in a complex path. Inadequately resin wetted and improperly cured fibers lack the enhanced structural integrity and reliability required for high performance applications. This was a serious problem for Watertown researchers due to the laboratory's heavy research in the field of composites for military applications.

In January 1985, U.S. Composites received a patent for their innovative solution: the invention of a Resin Applicator Ring

(RAR), that enables effective resin impregnation of moving fibers in a controlled environment, thus ensuring satisfactory braiding.

The RAR system was used by the Army to produce subscale trail arms for the lightweight howitzer, followed by the production of full-scale bore evacuators for the 120mm M256 cannon on the Abrams tank. With a fabrication time/cost savings of approximately 50%, these RAR system-produced evacuators were expected to replace filament-wound type classified evacuators.

Sixty % of the cumulative sales of U.S. Composites since the completion of the SBIR contract have been the direct result of the SBIR research. U.S. Composites has gone on to develop a variety of high performance components, including: a jet engine component, rocket motor cases, aircraft and marine propellers, high pressure hoses, composite coiled tubing for the oil and infrastructure industries and proprietary products for the medical and sporting goods industries.

A second company, Universal Energy Systems, Inc. of Dayton, Ohio, developed diamond-like carbon (DLC) coatings to mitigate rain and insect-induced erosion problems occurring with optical systems of airborne vehicles as well as sand-generated erosion in tactical ground vehicles and problems involving optical systems operating in saltwater spray and chemically corrosive environments.

An SBIR subcontractor, J.A. Woollam Company of Lincoln, Nebraska, developed the Variable Angle Spectroscopic Ellipsometer (VASE) which was used to characterize the DLC film produced by Universal Energy Systems. The prototype VASE was a Phase II deliverable to MTL. Employed in thin film optical characterization, R&D and quality control applications, the VASE is capable of measuring: film thickness in multilayer stacks; optical constants of films and bulk materials; surface and interface roughness; alloy fractions; and implantation damage.

A groundbreaker in the development of thick organic composite materials for ground vehicle applications, MTL early on recognized the need for a new nondestructive inspection technique for quality assurance. Responding to a SBIR need solicitation, Radiation Monitoring Devices (RMD) of Watertown, Massachusetts, developed an instrument to measure the fiberglass plies in composite armor panels. The resulting SBIR technology was a portable system based upon radiation back-scatter techniques.

Demonstrating the multiple possibilities for spin-off applications, RMD has developed: an on-line glass analyzing system to perform quality assurance radiation testing on TV picture tubes; a system to measure the composition of brakeshoe linings which in turn, will provide data on brake function performance and life; and an instrument to measure the amount of lead paint on the walls and ceilings of Federally owned housing units, with a time savings over current methods by a factor of 10.

MTL concerned itself not only with the quality assurance of composite materials but also sponsored an SBIR effort aimed at facilitating the introduction of advanced composite materials

into U.S. Army/DoD systems and fostering industrial applications. Materials Sciences Corporation (MSC) of Spring House, Pennsylvania, conducted a combined analytical and experimental verification effort and developed improved specimen designs to test composite materials. The experimental phase was performed by the University of Wyoming, the subcontractor. The conditions considered included: tension, compression, in-plane shear, combined stress, and interlaminar shear and fracture. The results have been incorporated into MIL-HDBK-17. In April 1990 the Federal Aviation Administration (FAA) began funding a three-year follow-on (Phase III) effort to incorporate certification requirements of small and transport airplanes and helicopters into MIL-HDBK-17B (Polymer Matrix Composites) (see section on Standardization).

Another company reaching Phase III success under MTL sponsorship is the Information Research Laboratory of North Dartmouth, Massachusetts. IRL developed a high-resolution, nondestructive evaluation (NDE) system based on ultrasonic spectroscopy and supported by innovative signal processing and pattern recognition methods.

Because of the hazards associated with the depleted uranium alloys used for penetrators MTL/ARL has explored the possibility of obtaining tungsten alloys with improved ballistic properties (see High Density Materials for Armor-Piercing Projectiles under Armaments). Under a SBIR need solicitation, Ultramet Corporation, based in Pacoima, California, developed a means of uniformly coating metallic and ceramic powder particles (as small as 5.0 microns in diameter) with metallic or ceramic matrices to produce a composite powder. An innovative high pressure, low temperature/time process is then used to consolidate the powder without appreciable grain growth (grain growth increases the contact area between tungsten particles and tends to increase potential crack initiation sites). The product is a composite material of substantially higher strength, uniformity and fracture toughness than similar materials produced by standard liquid phase sintering techniques.

During the Persian Gulf War, U.S. Army personnel were gravely concerned about the chemical warfare threat. At the time of the war's outbreak, the El Cajon, California based Sunrez Corporation was engaged in SBIR Phase II contract work to produce effective field repair kits for battle damaged vehicles. MTL was to conduct the field evaluations. Utilizing a bonded fiberglass patch for larger holes and patch putty containing fiberglass fibers for smaller holes, the main function of the repair kits is to seal holes in battle damaged vehicles to restore chemical agent resistance and moisture protection. Rapid Phase III success was achieved when MTL informed appropriate U.S. Army personnel about this project's potential, resulting in TACOM placing substantial orders for both kits and patch putty. Possible additional applications for the repair kit range from the repair of aircraft, ground vehicles, boats and pontoons to the sealing of holes in pipes.

A high-risk, high-technology program emphasizing innovation at both the conceptual and developmental levels, SBIR has produced, and continues to produce, significant numbers of notable products and processes, to the mutual benefit of involved companies, the United States and other countries. These successes are to a large degree attributable to the role that scientists and engineers of the Watertown labs have played in developing solicitation topics, evaluating proposals and technically monitoring and assessing the SBIR contracts. As product champions, Watertown personnel help the United States Government to reap maximum benefit from SBIR-developed innovations while fostering the economic health and entrepreneurial nature of America's small firms.

MILITARY TECHNOLOGY TRANSFER THROUGH COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS (CRDA'S)

Congress enacted the Federal Technology Transfer Act of 1986 for the purpose of enhancing the nation's economic security and global industrial competitiveness. It mandates Governmental collaboration with the private sector, through Cooperative Research and Development Agreements (CRDA's) targeted toward rapid commercialization of applicable and/or promising technology developed and/or conducted at Federal Laboratories.

The Act was signed into law (PL 99-502) on October 20, 1986. Rapid implementation was mandated to all Federal Agencies, including DoD, through Executive Order No. 12591 and DoD Regulation 3200-12-R-5, both issued in 1987. DoD regulation mandates delegation of authority to Lab Directors and provides for a minimum 20% of royalties to in-house Inventors. Army AR 70-57 "Military-Civilian Technology Transfer" implements the Act and structures the Office of Research and Technology Application (ORTA) in each laboratory to manage the CRDA process. Since its inception, the Watertown laboratories have actively pursued CRDA's leading to commercialization of materials technologies developed initially for defense purposes. Up until the time when the Watertown staff began to decline severely due to function transfers and personnel separations associated with the closing, the Watertown lab more than contributed its proportionate share of CRDA's to the ARL totals. The thirteen completed or active contracts include agreements with such prominent companies as: Dow Chemical, Owens Corning, Ceradyne Inc. and PPG Industries, Inc.

Statistics alone are not enough. It is the economic, social and technical consequences that make the difference. Small businesses will undoubtedly earn significant advantages via the use of laboratory expertise and facilities. Some have already done so very successfully and have already attracted a widening circle of customers and experienced significant increase in market share.

Potential Market Spin-offs cover a wide range of applications, some offering a globally competitive edge derived from the new innovations in either the materials or the processing techniques. One small business recently gained global market dominance with a new composite hockey stick, currently used by the U.S. Olympic Team. Another Consortium CRDA, under negotiation, is seeking rapid commercialization of a 1994 patent on a forearm crutch, far more user-friendly to those with chronic leg disabilities. Other examples include: sporting goods (wind surfer masts and golf clubs); lightweight printing rollers and shafts; laser-guide imaging tools used in fabricating thick composite structures, creating huge savings in manual labor; composite wind turbine blades much lighter in weight and of much longer service life; phase-shift ceramics formulations offering significantly improved military and commercial antenna designs for either land or air communication systems; advanced ceramic bearings requiring no lubrication and having a much longer service life; ion-implantation, doubling the service life of many cutting tools; electron beam assisted and chemical thin-film vapor deposition, eliminating serious pollution problems; new NDT techniques...etc.

Watertown has also formed broad-based partnerships with academic institutions, e.g., U of Del., MIT, UMass, Penn State, U of NH, RPI, VPI and Johns Hopkins. These CRDA's should generate and renew a more intensified level of scientific collaboration, open opportunities for greater exchange among senior research personnel, encourage greater university student access to our research staffs and facilities, create/enhance opportunities for more student aid and stimulate as well as facilitate continued academic retraining and advanced learning among our own bench scientists and engineers, besides jointly creating unlimited opportunities for marketable technology.

Moreover, our Technology Transfer Program encourages and assists toward consortial Technology Reinvestment Program (TRP) participation. Most importantly, under the present difficult Transition circumstances, the program has already induced and enhanced the opportunity for earlier placement of our transferee scientists and engineers at several universities near our future location in Aberdeen.

In summary, the Technology Transfer Program has exceeded all expectations and is expected to increase the number of successful Government - business and Government - academic cooperative agreements being implemented in the future.

CONCLUSION

As this historical compilation of Watertown's scientific and technological contributions comes to an end, the question of Watertown's uniqueness still remains to be examined. DoD laboratories are at somewhat of an advantage in that they are privy to a more holistic view of technology, since companies will discuss aspects of research with the government that they are unwilling to divulge to competitors, trusting the government to maintain the confidentiality of proprietary information. Beyond this generic edge, Watertown possessed a superb geographic location, in the heart of the Boston area's academic-research-business corridor, as discussed in this book's introduction. Although having an important effect on the performance of Watertown's mission these were factors extrinsic to Watertown. What were the internal explanations for Watertown's eminency?

One part of the answer lies in the range of disciplines and divisions assembled at Watertown. As the responsible agency for developing, maintaining and implementing materials specifications for all three services, Watertown was dependent on the close working arrangement that had evolved among various operations co-located at Watertown's laboratories. For example, if the mechanical design experts, composites and metals researchers had been broadly dispersed rather than concentrated at Watertown, it is likely that such major accomplishments as the world's first Composite Infantry Fighting Vehicle may not have reached fruition. Watertown was one of a very few laboratories, and the only Army lab, which could offer from basic research to prototyping capabilities for a wide variety of disciplines. In Watertown's foundry steel could be melted to Watertown specifications, forged, then rolled, heat treated, welded and ballistically tested; with feedback guiding the prototype process. The metallurgical A to Z range of services was mirrored in composites and other divisions. A material could be taken from fibers or powders to an end item. With a heavy interest in specifications and testing, Watertown was one of a handful of laboratories which pioneered in the development of standard testing techniques as well as the establishment of materials specifications.

Another strength of Watertown, contributing to its uniqueness, was the cumulative knowledge accruing from decades, indeed, over a century, of research activity. A striking finding during the research process of writing this book was the number of interviewees and contributors who commented upon the mentorship relations which routinely occurred at Watertown. Visionaries not only gave birth to, nurtured and maintained programs, but they also encouraged young researchers and even in retirement made available their knowledge and problem solving skills to current research teams. Experience and youth combined in a dynamic investigative research and development mode.

Watertown was also noted for its cooperation with other Army facilities, other DoD and government organizations and private industry. The entire laboratory structure repeatedly spurred private research through its R&D leadership, whether as exhibited

in the laboratory work itself, through conference leadership, cooperative agreement participation or through its seminal papers and handbook publications. Although Watertown's quest always centered on better materials and materiel for Army needs, much of its research and development activity underwent a process of technology transfer, with new non-military applications extending benefits into the private sector.

In gathering material for this book a central research question had been the effect of organizational changes on research conducted at Watertown, given Watertown's many, and externally imposed, evolutions. Time and time again, Watertown personnel, whether or not still employed at Watertown, pointed to their teams' ability to meet time constraints and to maintain program momentum despite organizational changes.

The contributions of recent years are all the more striking given that they occurred against a backdrop of personnel and budgetary cuts. Watertown underwent the combined effects of base closure and relocation of functions; the attrition of staff and downsizing; funding restrictions; and the necessity to devote time and energies to new facility planning. More work was done on contract and piecemeal, adversely affecting productivity. Researchers experienced delays in attempting to initiate and carry out work. During the last year at Watertown, with the move to Aberdeen, the working environment became exceptionally difficult. Because entire groups were not necessarily moved as a unit, the move was accompanied by discontinuity and difficulty in bringing team energies together around a concept or problem. The result was a decrease in synergism.

Individuals and families experienced tremendous personal emotional strain and professional disruption as the result of the closing of Watertown. As one long-time Watertown researcher commented, "We're so good they're shutting us down." Some chose not to move with the mission because of the prolonged uncertainties and a personal sense of bitterness. Others reluctantly severed their connections with military research because of the perplexing problems of swing space and permanent relocation when double moves appeared not to be in the best interests of a spouse's career or children. Property sale considerations and responsibility for the care of elderly parents caused some to seek new careers. One solution has been for some couples to agree to weekend commuter marriages until facilities are established in permanent locations. Many face additional financial burdens regardless of whether they choose to relocate with the mission or to remain behind. The dilemma of whether or not to go was taken out of the hands of many Watertown employees when entire categories of support personnel were not offered transfers due to downsizing and the need to avoid duplication of job categories at the new site.

Yet despite less than ideal work conditions, Watertown was able to make a significant contribution to the United States' Desert Storm effort. Watertown accelerated the development program for an improved tow bar for recovering damaged tanks,

identifying the cause of failure in the existing tow bar and developing options using composite materials and higher strength steels (see History of the Lightweight Steel Tow Bar System). Another major activity was the advanced Laser Protection Program which focused on the solarization of Ballistic Laser Eye Protection Spectacles (see Laser Protection). A third major area of contribution was the analysis of sources of failure and/or deterioration in U.S. equipment in South West Asia. These analyses included failure in the AH-64 Apache helicopter rotor system; a fuel control pump bellows from a CH-47D Chinook helicopter; the thermal protective coating on MK83 general purpose bombs; a component of a bomb-armer mechanism used on Navy aircraft; and the deterioration of tires from heat and UV radiation. Related to all the foregoing activities was a study of the composition of desert sand, the finer particle size of which posed materiel and materials failure problems not generally encountered elsewhere.

The Army Laboratories at Watertown which repeatedly rallied behind, and helped to shape, the nation's military effort in times of international strife, civil war and Cold War, no longer echo with the pendulum's swing of the Charpy machine. Researchers no longer huddle over diagrams of tank components or make preparations for field trips in failure analysis. The foundry's embers have died out, and ingots no longer stand testimony to a nation's inquisitive bent and military might. Workmen no longer scramble over gun carriage mounts, and high ceilinged buildings are eerily empty. Searches are no longer conducted in the now dismantled technical library, a corporate memory fragmented and waiting to be made whole again. The excitement of exploring the possibilities of new materials and pushing the limits of existing ones will occur elsewhere.

Watertown, the site, remains, however. In preparing the facility for closure the Army addressed the future of the site by engaging in such activities as conducting environmental investigations, preserving cultural resources and working with the local community to help them plan for the reuse of the site.

The vision which the community had for the Arsenal site was for it to provide the town with job opportunities and tax revenues while also improving the character of its public environment. But to be successful, planned commercial, residential and public uses must be combined in a coherent physical plan which is sensitive to the character of surrounding residential neighborhoods, preserves the site's significant historic structures,* incorporates open space as an integral part of the development of the site, improves access to existing open spaces such as Arsenal Park, and creates better physical

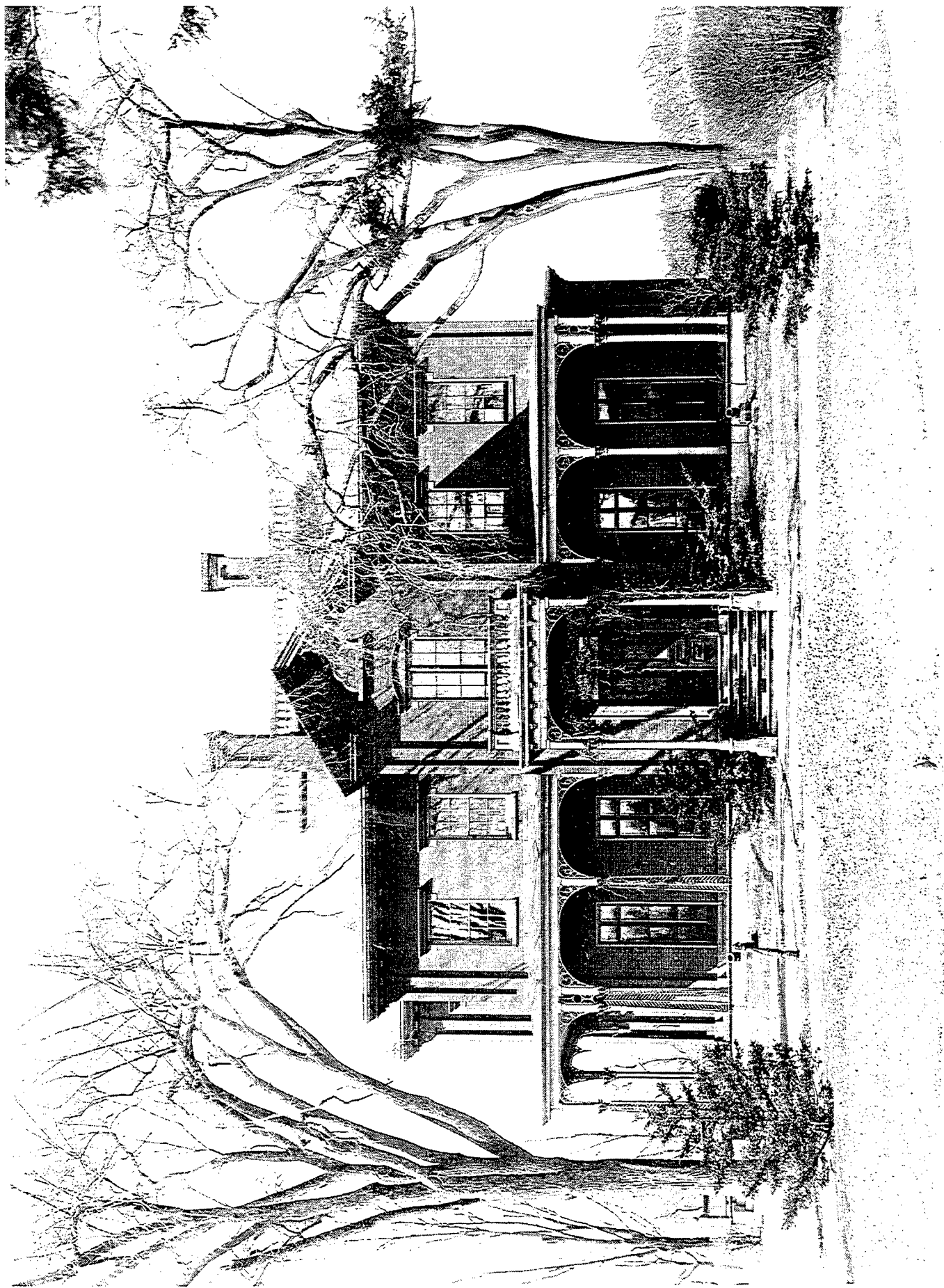
* The Watertown site includes buildings and landscapes that date from 1851 to 1940, and together they have been defined as constituting a Historic District that is eligible for inclusion in the National Register of Historic Places.

connections between the entire community and its beautiful open space network along the Charles River. To deal with these challenges, the town established the Arsenal Reuse Committee in 1989 to represent it in discussions with the Army and federal and state agencies regarding closure and the subsequent site clean-up and to develop a proposed reuse plan for the site.

The closing process at Watertown and redevelopment plans were facilitated by the five-point initiative announced by President Clinton in July of 1993. One of the initiatives was to name a base transition coordinator at each closing base to serve as a central federal point of contact. The coordinator was given the authority to bring problems and unique situations directly to the highest levels of federal government for expeditious resolution. Another was jobs-centered property disposal. This called for replacing the existing fair market value restriction with a low or no-cost disposal option when reuse plans call for vigorous economic development geared toward creating jobs. A third initiative of President Clinton's was fast-track clean-up. Under this provision base closure clean-up teams were formed and empowered to make common-sense clean-up decisions so as to avoid lengthy hierarchical reviews and inter-agency communication problems. Another point of the initiative plan was to provide easy access to transition and redevelopment assistance by eliminating red tape. The final initiative in the President's plan was directed at making available larger economic development planning grants to communities hosting closing military bases.

Based on the technical analysis undertaken by a consultant team, the goals of the Arsenal Reuse Committee and the concerns of local citizens, the development model which emerged that offers the community of Watertown the most significant benefits with acceptable impacts is to develop the site as an integrated, mixed-use development with a research and development center, rehabilitated housing, cultural and community use, and limited retail use. The physical design is expected to make the site and river more accessible to the community. The completion of such a plan will bring the former Army laboratory site into the 21st century, benefiting the area's, and the nation's, economy and quality of life.

Plans have been formulated for the Commander's house to become a museum, housing records and artifacts related to the site's history and to the advances which occurred at Watertown. Such a repository in so symbolic a location makes feasible the possibility of former members of Watertown's staff and the town of Watertown working together to preserve the heritage of Watertown's contributions to science and technology. Because of changing national and international dynamics Watertown is once again undergoing a transformation. The future, however, is built upon the past.



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APPENDICES

Dedicated civilian and military personnel made Watertown a vital link in the Nation's defense for 179 years.

1816-1967	The Watertown Arsenal, originally established at Charlestown by an Act of Congress in 1794
c. 1830-1962	The Watertown Arsenal Laboratories
1954-1962	The Ordnance Materials Research Office
1962-1967	The Army Materials Research Agency
1967-1985	The Army Materials and Mechanics Research Center
1985-1992	The Materials Technology Laboratory
1992-1995	The Army Research Laboratory, Materials Directorate

APPENDIX A

COMMANDING OFFICERS

WATERTOWN ARSENAL

Capt. George Talcott	23 Sep 1816-9 July 1820
Maj. Abram R. Wooley	9 July 1820-22 Sep 1821
1st Lieut. David T. Welch	22 Sep 1821-16 May 1823
Lieut. John W. Thompson	16 May 1823-31 Dec 1824
Maj. Henry K. Craig	10 May 1825-1 Sep 1838
Maj. Mann P. Lomax	1 Sep 1838-27 Mar 1842
Capt. William A. Thornton	3 May 1842-3 Sep 1851
Maj. Edward Harding	3 Sep 1851-10 Oct 1854
Lieut. Col. James W. Ripley	1 Nov 1854-28 Feb 1855
Capt. Robert A. Wainwright	18 May 1855-12 May 1859
Capt. Thomas J. Rodman	12 May 1859-18 July 1865
Maj. Charles P. Kingsbury	18 July 1865-12 Jan 1871
Lieut. Col. Theodore T.S. Laidley	11 Apr 1871-29 Nov 1882
Maj. Francis H. Parker	1 May 1883-20 Nov 1889
Lieut. Col. Daniel W. Flagler	30 Nov 1889-2 Feb 1891
Lieut. Col. William A. Marye	13 Jun 1891-12 Aug 1891
Maj. James W. Reilly	1 Feb 1892-11 Sep 1900
Maj. John G. Butler	11 Sep 1900-22 Jan 1904
Maj. Ira MacNutt	22 Mar 1904-29 Apr 1905
Maj. Frank E. Hobbs	29 Apr 1905-17 Jul 1907
Maj. Colden L.H. Ruggles	18 Jul 1907-1 Feb 1908
Col. Charles B. Wheeler	2 Feb 1908-2 Mar 1917
Lieut. Col. Tracy C. Dickson	3 Mar 1917-8 Jan 1918
Col. Charles M. Wesson	9 Jan 1918-13 Oct 1918
Brig. Gen. Tracy C. Dickson	14 Oct 1918-17 May 1932
Col. Glen F. Jenks	17 May 1932-26 Apr 1937
Col. Charles T. Harris, Jr.	3 May 1937-31 Jul 1937
Brig. Gen. Rolland W. Case	11 Aug 1937-4 Nov 1941
Col. John Mather	4 Nov 1941-14 Dec 1945
Col. William B. Hardigg	14 Dec 1945-23 May 1946
Col. William R. Gerhardt	23 May 1946-28 Feb 1949
Brig. Gen. Carroll H. Detrick	1 Apr 1949-21 July 1951
Col. Benjamin S. Mesick	1 Sep 1951-1 Sep 1954
Col. Alden P. Taber	1 Sep 1954-1 Jul 1956
Col. Richard M. Hurst	1 Jul 1956-11 Apr 1959
Lieut. Col. Robert R. Lutz	12 Apr 1959-9 Jun 1959
Col. Charles E. Rust	10 Jun 1959-18 May 1960
Col. Robert B. Braid	19 May 1960-18 Aug 1963
Col. Erik W. Jordahn	19 Aug 1963-27 Sept 1965
Lieut. Col. Charles A. Conlin	28 Sept 1965-20 Nov 1965
Col. Oscar C. Tonetti	21 Nov 1965-30 Jun 1967

AMMRC

Col. Dimitri A. Kellogg	1 Jul 1966-26 Aug 1967
Brig. Gen. William M. Mantz	27 Aug 1967-30 Oct 1967
Col. Clifford T. Riordan	1 Nov 1967-21 Mar 1968
Brig. Gen. Felix J. Gerace	22 Mar 1968-19 Sep 1968
Col. James G. Bennet	20 Sep 1968-6 Jan 1969
Lieut. Col. Joseph B. Mason	7 Jan 1969-30 Apr 1970
Capt. David T. Rankin	1 May 1970-1 Jul 1970
Lieut. Col. John W. Gillespie	2 July 1970-3 Aug 1971
Maj. Thomas E. Ross	4 Aug 1971-23 Aug 1971
Maj. Kenneth I Kawano	24 Aug 1971-30 Apr 1972
Lieut. Col. Robert B. Henry	1 May 1972-30 Jun 1975
Lieut. Col. William C. Harrison	1 Jul 1975-14 Sep 1975
Lieut. Col Edward E. Chick	15 Sep 1975-31 Jan 1978
Col. William R. Benoit	1 Feb 1978-29 Nov 1979
Col. George W. Sibert	29 Nov 1979-8 Jul 1983
Col. Lawrence C. Ross	8 July 1983-30 Aug 1985

MTL

Col. John E. Kemspter	30 Aug 1985-12 Jun 1987
Maj. Melvin E. Adams	12 Jun 1987-23 Aug 1987
Col. Donald R. Kenney	24 Aug 1987-30 Nov 1989
Maj. Melvin E. Adams	1 Dec 1989-28 Feb 1992

ARL-MD

Lieut. Col. James T. Naughton	1 Mar 1992-13 Dec 1993
Maj. Jeffrey I. Stiefel	13 Dec 1993-30 Sep 1995

APPENDIX B
LABORATORY DIRECTORS
OF
AMRA, AMMRC, MTL, and ARL-MD

Dr. James L. Martin	July 1962-June 1967
Mr. Joseph F. Sullivan	July 1967-September 1968
Dr. Evaldus P. Scala	September 1968-August 1969
Mr. Joseph F. Sullivan	August 1969-February 1970
Dr. Alvin E. Gorum	February 1970-January 1976
Dr. Edward S. Wright	January 1976-February 1992
Dr. Gordon A. Bruggeman	February 1992-September 1992
Mr. Lawrence D. Johnson	October 1992-present

APPENDIX C

ARMY R & D AWARDS

1961-ALBERT P. LEVITT-In recognition for his engineering leadership in establishing and directing the high-temperature materials research programs at Watertown.

1965-MILTON LEVY-For development of a lightweight ceramic composite armor system; for his contribution in the development of an antigalling coating for titanium; and for an oxidation-resistant composite coating system for the molybdenum nose cone.

1968-JIRO ADACHI and JOHN F. MESCALL- For establishing experimental-theoretical stress analysis of cylindrical shells capped with torispherical end closures, which permit efficient design against rupture and buckling under service conditions.

1970-FORREST C. BURNS, GRACE L. PRIEST, AND HOMER F. PRIEST- For establishing a new system for quality inspection of pellet weight in M34 primers which advances a state-of-the-art in neutron activation analysis and high-rate inspection of components.

1971-DENNIS J. VIECHNICKI AND FREDERICK SCHMID- For the development of new crystal growing techniques permitting growth of single crystal sapphire six inches or greater in diameter for transparent armor and optical applications.

1973-FORTUNATO J. RIZZITANO, JACOB GREENSPAN, and DAVID A. COLLINGS- In recognition of their work on structural uranium alloy systems including small-caliber armor penetrators and the center body of the XM 673 8-inch nuclear sound.

1974-DONALD R. MESSIER and PHILIP WONG- In recognition of research accomplishments on silicon nitride for gas turbine and radome applications which have led to significant improvements in the technology of production or reaction-bonded silicon nitride.

1976-FRANCIS C. QUIGLEY, ARTHUR W. AYVAZIAN, ROBERT H. FROST, and DINO J. PAPETTI-For outstanding achievements in developing and

1976-JOHN F. MESCALL, PAUL V. RIFFIN, ANNA M. HANSEN, CHARLES J. POLLEY, JOSEPH CASAZZA, and DANIEL RYAN (6 man team)- For

demonstrating a new concept that evolved from computer studies based on a double-wall fragmentation casing which dramatically improves both the effectiveness and reliability of fragmentation devices.

1977- ANTHONY L. ALESI, EUGENIO DE LUCA, and JOSEPH J. PRIFTI-For

developing a production process for molding thick-walled, large size armor panels from multiple plies of unidirectionally oriented polypropylene radomes against fragmenting munitions.

1978-ROBERT E. SACHER, GARY HAGNAUER, and JAMES E. SPROUSE-For

developing techniques for selection process of fiberglass reinforced epoxy resin systems which provide quality control and assurance for Army programs where strength, lightweight, and corrosion resistance are important.

1979-DENNIS J. VIECHNICKI and JAROSLAV L. CASLAVSKY-For developing

a new method of producing Nd: YAG large single crystals resulting in cost reduction in producing laser rods of the Army's range finding and laser guidance systems.

1980-ALBERT P. LEAVITT and EUGENE DI CESARE-For research that

resulted in the development and patenting of graphite fiber reinforced magnesium composites.

1980-GEORGE E. GAZZA-For development of new methods for producing

near net shape Si_3N_4 based ceramic components for heat engines which are critical in engine development programs.

1981-JANET S. PERKINS-In recognition of her work providing

superior laser protection using tungsten bearing resins. This study will impact on the design of future laser barriers.

1981-JAMES W. MACAULEY and NORMAN D. CORBIN- In recognition of the

contribution to the tech base in developing nitrogen stabilized cubic alumina (ALON) and a method for its fabrication by a sintering process.

1982-JACOB GREENSTEIN, RUSSEL G. HARDY, JAMES T. GARVIN, and DAVID

S. KIEFER-For R & D leading to special techniques to attach rotating bands of conventional copper and copper alloy

to large caliber projectiles of high performance titanium alloys.

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1982-JAMES M. SMITH-For design, fabricating, and testing an advanced ultrasonic testing instrument that reduced the inspection time for certain products as artillery shell rotating bands by about a factor of ten.

1983-JOSEPH J. PRIETI, EUGENIO DELUCA, and DINO J. PAPETTI-For developing four advanced, low-cost, generic, lightweight, armor materials systems for crew protection in ground vehicles and aircraft.

1983-JAMES W. MACAULEY NORMAND D. CORBIN, PHILIP WONG, and THERESA M. RESETAR-For the successful demonstration of the use of solid state exothermic gasless reactions to produce ceramic materials with minimal energy consumption.

1985-DONALD R. MESSIER and EILEEN DEGUIRE-For developing advanced transparent oxynitride glasses, a significant contribution to solving the Army's requirement for improved scratch resistant and ballistically efficient ballistic armor.

1987-DENNIS J. VIECHNICKI, WILLIAM A. BLUMENTHAL, CARL A. TRACY, HOLLY A. SKEELE, MICHAEL J. SLAVIN, and JEFFREY J. GRUBER (6 man team)-For research and advanced development of titanium diboride as a superior yet cost effective material for future heavy armor applications.

1987-CHESTER V. ZABIELSKI- For development of a family of thermomechanically processed DU-3/4Ti alloys with greatly increased yield and tensile strength.

1992-STANLEY E. WENTWORTH, PAUL R. BERQUIST, MICHAEL S. SENNETT, and WALTER X. ZUKAS (5 man team)-For contributions to adhesive bonding science and technology in support of the AMC Adhesive Bonding Improvement Initiative. This work will provide basis for service life predictive models of adhesively bonded structures in Army materiel.

SAGAMORE ARMY MATERIALS RESEARCH CONFERENCE PROCEEDINGS

- 1st: RESIDUAL STRESSES (Proceedings not Published)
- 2nd: STRENGTH LIMITATIONS OF METALS
- 3rd: MATERIALS EVALUATION IN RELATION TO COMPONENT BEHAVIOR
- 4th: HIGH TEMPERATURE MATERIALS, THEIR STRENGTH POTENTIALS AND LIMITATIONS
- 5th: MATERIALS IN SPACE ENVIRONMENT
- 6th: COMPOSITE MATERIALS AND COMPOSITE STRUCTURES
- 7th: MECHANICAL AND METALLURGICAL BEHAVIOR OF SHEET METALS
- 8th: MECHANISMS OPERATING IN METALS AT ELEVATED TEMPERATURES
- 9th: FUNDAMENTALS OF DEFORMATION PROCESSING
- 10th: FATIGUE: AN INTERDISCIPLINARY APPROACH
- 12th: STRENGTHENING MECHANISMS: METALS AND CERAMICS
- 13th: SURFACES AND INTERFACES I: CHEMICAL AND PHYSICAL CHARACTERISTICS
- 14th: SURFACES AND INTERFACES II: PHYSICAL AND MECHANICAL PROPERTIES
- 15th: ULTRAFINE GRAIN CERAMICS
- 16th: ULTRAFINE GRAIN METALS
- 17th: SHOCK WAVES
- 18th: POWDER METALLURGY FOR HIGH-PERFORMANCE APPLICATIONS
- 19th: BLOCK AND GRAFT COPOLYMERS
- 20th: CHARACTERIZATION OF MATERIALS IN RESEARCH: CERAMICS AND POLYMERS
- 21st: ADVANCES IN DEFORMATION PROCESSING
- 22nd: APPLICATION OF FRACTURE MECHANICS TO DESIGN
- 23rd: NONDESTRUCTIVE EVALUATION OF MATERIALS
- 24th: RISK AND FAILURE ANALYSIS FOR IMPROVED PERFORMANCE AND RELIABILITY
- 25th: ADVANCES IN METAL PROCESSING
- 26th: SURFACE TREATMENTS FOR IMPROVED PERFORMANCE AND PROPERTIES
- 27th: FATIGUE: ENVIRONMENT AND TEMPERATURE EFFECTS
- 28th: RESIDUAL STRESS AND STRESS RELAXATION

- 29th: MATERIAL BEHAVIOR UNDER HIGH STRESS AND ULTRAHIGH LOADING
RATES
- 30th INNOVATIONS IN MATERIALS PROCESSING
- 31st: MATERIALS CHARACTERIZATION FOR SYSTEMS PERFORMANCE AND
RELIABILITY
- 32nd: ELASTOMETERS AND RUBBER TECHNOLOGY
- 33rd: CORROSION PREVENTION AND CONTROL
- 34th: INNOVATIONS IN ULTRAHIGH-STRENGTH STEEL TECHNOLOGY
- 35th: THE SCIENCE AND TECHNOLOGY OF ADHESIVE BONDING
- 36th: THICK SECTION COMPOSITE TECHNOLOGY
- 37th: STRUCTURAL CERAMICS
- 38th: ELECTROMAGNETIC, ELECTRO-OPTICAL, AND ELECTRONIC MATERIALS
- 39th: THE SCIENCE AND TECHNOLOGY OF FIRE RESISTANT MATERIALS
- 40th: METALLIC MATERIALS FOR LIGHTWEIGHT APPLICATIONS
- 41st: INTELLIGENT PROCESSING OF MATERIALS

THE ARMY SYMPOSIUM ON SOLID MECHANICS

The Army Symposium on Solid Mechanics has been held biannually since 1968 with the purpose of focusing on solid mechanics research which impacts defense systems needs. The Symposium at the beginning was sponsored by the Technical Working Group (TWG) for Mechanics of Materials, one of the nine TWGs of the Materials Advisory Group of the Army Materiel Command. The Symposium, while sponsored by the Army, involved nearly from the start all three Armed Services, other government agencies, universities, research institutes, and industry, since mechanics research/design problems are not unique to a single Service, agency or industry.

Watertown (AMMRC) in its role as the Army's lead laboratory for solid mechanics played a major part in the Symposium from the first. In the mid 1970s when the TWG's ceased to function, Watertown picked up the leadership in organizing the Symposium. This continued through 1992 when, with the establishment of ARL, Watertown invited the Weapons Technology and Vehicle Structures Directorates of ARL and the Army Research Office to participate in sponsorship of the 1993 Symposium.

There have been thirteen Symposia in the series thus far. These are listed below:

1968	Solid Mechanics
1970	Lightweight Structures
1972	Role of Mechanics in Design--Ballistic Problems
1974	The Role of Mechanics in Design--Structural Joints
1976	Composite Materials: The Influence of Mechanics of Failure on Design
1978	Case Studies on Structural Integrity and Reliability
1980	Designing for Extremes: Environment, Loading, and Structural Behavior
1982	Critical Mechanics Problems in Systems Design
1984	Advances in Solid Mechanics for Design and Analysis
1986	Lightening of the Force
1989	Mechanics of Engineered Materials and Applications
1991	Synergism of Mechanics, Mathematics, and Materials
1993	Solid Mechanics Research Achievements Relevant to Defense Systems Needs

Army Materials Technology Conference

The Army Materials and Mechanics Research Center initiated a new conference series in the fall of 1972 with the express purpose of bringing to industry and to academic and Governmental agencies the most recent advances in materials technology.

1st: Solidification Technology

2nd: Ceramics for High Performance Applications I

3rd: Physical Metallurgy of Uranium Alloys

4th: Advances in Joining Technology

5th: Ceramics for High Performance Applications II

6th: Ceramics for High Performance Applications III

APPENDIX G
GLOSSARY OF ACRONYMS

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BRAC	Base Realignment and Closure Commission
BRL	Ballistic Research Laboratory
BSTO	Barium Strontium Titanate
CAT	Computerized Axial Tomography
CAV-ATD	Composite Armored Vehicle-Advanced Technology Demonstration
CCA	Ceramic Composite Armor
CD-ROM	Compact Disc-Read Only Memory
CECOM	Communications and Electronics Command
CERL	Construction Engineering Research Laboratory
CIA	Central Intelligence Agency
CIFV	Composite Infantry Fighting Vehicle
CIMAP	Crack Inspection Map
CMRL	Combat Materiel Research Laboratory
CONUS	Continental United States
CPC	Corrosion Prevention and Control
CRDA	Cooperative Research and Development Agreement
CS3	Computerized Standardization Search Systems
CTX	Center for Excellence
CVD	Chemical Vapor Deposition
CW	Chemical Warfare
DA	Department of Army
DARCOM	Department of the Army Development and Readiness Command
DARPA	Defense Advanced Research Project Agency
DHSA	Dual Hardness Steel Armor
DLC	Diamond-Like Carbon
DMR	Defense Management Review
DMWR	Depot Maintenance Work Requirements
DOD	Department of Defense
DOP	Depth of Penetration
DRI	Dayton Research Institute
DSSP	Defense Standardization and Specification Program
DU	Depleted Uranium
EAMTP	Experimentally Acceptable Treatment Process
EF	Electric Furnace
EIS	Electrochemical Impedance Spectroscopy
ELI	Extra Low Interstitial
EM	Electromagnetic
ERIS	Exo-atmospheric Re-entry Intercept System
ESD	Engineering Standardization Division
ESR	Electroslag Remelting
FAA	Federal Aviation Administration
FCC	Face Center Cubic
FEM	Finite Element Method
FOG-M	Fiber Optic Guided Missile